APPENDIX C

TECHNICAL BASIS FOR DOSE MODELING EVALUATION

STANDARD REVIEW PLAN FOR THE REVIEW OF DECOMMISSIONING PLANS AND OTHER INFORMATION SUBMITTED TO SUPPORT THE RELEASE OF NUCLEAR FACILITIES

APPENDIX C

TECHNICAL BASIS FOR DOSE MODELING EVALUATION

CONTENTS

1.0 Introduction

1.1 Background

The NRC published on July 21, 1997, in the Federal Register (62 FR 39058) a final rule on "Radiological Criteria for License Termination" which was incorporated as Subpart E into 10 CFR Part 20. NRC Staff developed a draft regulatory guide, *Demonstrating Compliance with the Radiological Criteria for License Termination* (DG-4006) (NRC, 1998), and a draft document *Decision Methods for Dose Assessment to Comply With Radiological Criteria for License Termination* (NUREG-1549) (NRC, 1998a) in support of the final rule implementation. In addition, staff developed a screening code "DandD" for demonstration of compliance with the dose criteria in 10 CFR Part 20, Subpart E. On July 8, 1998, the Commission approved publication of the draft guidance DG-4006, the draft NUREG-1549, and the DandD screening code for interim use for a period of two years (i.e., July 8, 1998 through July 7, 2000) (NRC, 1998b). In addition, the Commission directed staff to (1) develop a standard review plan (SRP) for decommissioning, and provide the Commission with a schedule for the SRP; (2) maintain a dialogue with the public during the interim period; (3) address areas of excessive conservatism, particularly in the DandD screening code; and (4) develop a more user friendly format for the guidance (NRC, 1998b).

Staff has completed development of the SRP. Chapter 5 of the SRP is the module for staff review of the "Dose Modeling Evaluation." The current "Technical Basis Document" (TBD) is a supporting technical information document for dose modeling evaluation. It presents detailed technical approaches, methodologies, criteria, and guidance for staff review of dose modeling for demonstration of compliance with the dose criteria in 10 CFR Part 20, Subpart E. The current technical basis document has been developed through dialogue with the public (e.g., dialogue with stakeholders, licensees, Federal agencies, States, and interest groups). In this regard, staff conducted six public workshops and gave several presentations at professional national and international professional meetings, at stakeholders meetings, ISCORS, CRCPD, as well as presentations to ACNW. Within the past two years, staff has tested the DandD code for complex sites and addressed the issue of excessive conservatism in the DandD code. In addition, staff developed a new probabilistic DandD code (e.g., DandD Version 2) to reduce the excessive conservative approach in the previous code version. Further, staff developed RESRAD and RESRAD-BUILD probabilistic codes for site-specific analysis. Development of the probabilistic DandD and RESRAD/RESRAD-BUILD codes also responds to Commission direction to ensure that the risk-informed and iterative dose modeling approaches are maintained.

1.2 Brief Description and Scope

The current TBD should be used along with the SRP Chapter 5 "Dose Modeling Evaluation" for staff review of licensee's analysis for demonstration of compliance with the dose criteria in 10 CFR Part 20.1402 and §20.1403. Section 1.3 presents the iterative approach in dose modeling and decision framework methodology. This section would help reviewers to direct licensees for alternate options of more advanced dose assessment based on additional site characterization or based on ceratin remedial actions to reduce the overall dose at the concerned site. Section 2 presents acceptable approaches and staff use of look-up tables and screening models for

demonstration of compliance with the dose criteria using a screening methodology. Section 2 also discussed attributes of screening and site-specific analysis to evaluate the merits of both dose modeling approaches. Staff has identified the criteria for qualification of the site to accept this screening approach. Section 3 presents staff approaches for review of conceptual representation of the radioactive source material at the contaminated site. This section describes areas of reviews pertaining to existing radioactive material source and physical and chemical characteristics of the source material. In addition, the section presents recommended approaches for source-term abstraction for the purpose of performing dose analysis. Section 4 focus on areas of review and criteria for acceptance of pathways modification of the two generic critical group scenarios, the "resident farmer" and the "building occupancy" scenarios. In this context, Section 4 presents staff review of licensee's justifications for modification of default screening scenarios and associated pathways and approaches for establishing site-specific scenarios, critical groups, and/or sets of exposure pathways based on specific land, site restrictions, and/or site-specific physical conditions. Section 5 provides approaches for developing site-conceptual models for dose analysis. This section presents approaches for assimilation of data to establish a site conceptual model via the linkage of the source-term with the critical group receptor and use of applicable pathways and site characterization data and employment of applicable mathematical models to simulate and calculate release and transport of contaminants from the source to the receptor. The section also presents discussions of typical conceptual models used for DandD and RESRAD codes. The section also provides information regarding limitations of the DandD and RESRAD models and review areas to ensure compatibility of the site conceptual with the conceptual models embedded in the DandD and RESRAD codes. Section 6 presents approaches and criteria for staff acceptance of computer codes/models. In this regard, section 6 presents review aspects pertaining to codes/models specifications, testing, verification, documentation, and quality assurance/quality control (QA/QC) of the code used by the licensee. This section also addresses reviews applicable to embedded numerical models for the source-term, the exposure pathway models, the transport models, and the intakes or dose conversion models. The section also provides generic description and development of the DandD code particularly excessive conservatism of the DandD, version 1, code. It also describes approaches for development of probabilistic DandD Version 2 and examples of DandD code application. Section 6 also presents generic description of the deterministic RESARD/RESRAD-BUILD codes and approaches for the development of probabilistic RESARD & RESRAD-BUILD codes. It also provides examples for application and execution of the newly developed codes. Section 7 provides staff review of approaches for selection and modification of input parameters for dose modeling analysis. The section also lists default parameter distributions, default distribution types, and default parameter distribution values for the probabilistic DandD, RESRAD, and RESRAD-BUILD codes. Finally, section 8 of the TBD addresses the acceptable criteria for treating uncertainties in the dose modeling analysis. In this regard, staff review of issues pertaining to uncertainty and sensitivity, and staff recommended approaches for resolution of issues, are addressed. Policy positions are presented regarding approaches to uncertainty/sensitivity treatments and specific percentile dose-distribution selection (e.g., as regulatory limits) for the screening and site-specific analysis. Staff review of input parameter distributions for Monte Carlo analysis and generic description of sensitivity analysis including statistical techniques are also described.

The above TBD is intended for staff technical review of dose analysis methods and approaches and reviews of codes/models employed and associated pathways and parameters for demonstration of compliance with the dose criteria in 10 CFR Part 20 Subpart E. The contents of the TBD and may also be used by the licensees as guidance for acceptable approaches or methodologies to conduct dose modeling analysis. Further, the listed look-up tables and the newly developed codes/models may also be used by the licensees as applicable to their sites for demonstration of compliance with the license termination rule dose criteria.

1.3 Dose Modeling and Decision Framework Methodology

NUREG-1549 provides a summary of the decision framework and methodology for conducting dose assessments in support of license termination decisions. It also provides three separate discussions to illustrate the phased and iterative nature of assessments as increasing complexity occurs. What follows is both a summary of the steps of the decision framework and a set of examples to help users walk through most of the features of the dose modeling in the context of the decision support methodology.

Steps of the Decision Framework:

Refer to Figure C1.1 (from NUREG-1549) while reviewing the following steps of the dose modeling framework:

Step 1: The first step in a dose assessment involves gathering and evaluating existing data and information about the site, including the nature and extent of contamination at the site. Often, minimal information is all that is needed for initial screening analyses (e.g., a simple representation of the source of contamination). Specifically, information is needed to support the decision that the site is simple and is qualified for screening analysis (see section 2). However, reviewers should use all information about the site that is readily available. This step also includes definition of the performance objectives that must be met in order to demonstrate compliance with decommissioning criteria.

Step 2: This step involves defining the scenarios and pathways that are important and relevant for the site dose assessment (see section 4). For all assessments using DandD, the NRC has already defined the generic scenarios and pathways for screening. For site-specific analysis mode, DandD and RESRAD/RESRAD-BUILD codes may be used, in addition to other codes. These codes should allow the user to both select, and de-select, exposure pathways if certain pathways are not considered relevant due to site conditions (see section 4).

Step 3: Once scenarios are defined and exposure pathways identified, a basic conceptual understanding of the system is developed, often based on simplifying assumptions regarding the nature and behavior of the natural systems (see section 5). System conceptualization includes conceptual

and mathematical model development and assessment of parameter uncertainty. Using DandD for generic screening, the NRC has pre-defined conceptual models for the scenarios along with default parameter distributions (based on NUREG/CR-5512 Volumes 1 and 3) (Kennedy and Strenge, 1992; Beyeler et al., 1999). For site specific analysis the DandD and/or RESRAD/RESRAD BUILD conceptual model can be used after verification that the actual site conceptual model is compatible with the conceptual model of the code used.

Step 4: This step involves the dose assessment or consequence analysis, based on the defined scenario(s), exposure pathways, models, and parameter distributions. For generic screening, reviewers can accept look-up table (see section 2) and use the generic models and default parameter pdfs, simply by running DandD with the appropriate site-specific source term, leaving all other information in the software unchanged. Site-specific assessments allow the user to use other codes and change pathways and parameter distributions based on data and information obtained from the site. DandD and RESRAD/RESRAD-BUILD provide various plots and reports of the dose distribution based on Monte Carlo sampling of the input distributions.

Step 5: This is the first major decision point in the license termination decision process and involves answering the question of whether the dose assessment results from Step 4 demonstrate compliance with the dose criterion in 10 CFR Part 20, Subpart E (for unrestricted release, this is 25 mrem/y). NRC establishes the confidence required when interpreting the results from the probabilistic dose assessment. For instance, for screening analysis, licensees may need to demonstrate that the 90^{th} percentile value of dose is less than 25 mrem/y. If the results are below the limit, the licensee proceeds with Steps 6 and 7 to demonstrate ALARA requirements and initiate the license termination process defined by NRC in other guidance documents. Note that the DandD or RESRAD codes do not involve or automate these steps.

If the results are ambiguous or clearly exceed the performance objective, then the user must proceed to Steps 8 and 9.

Step 8: Full application of the decision framework involves defining all possible options the licensee might address in order to defend a final set of actions needed to demonstrate compliance with license termination criteria. Options may include acquiring more data and information about the site and source(s) of contamination in order to reduce uncertainty about the pathways, models, and parameters and thus reduce the calculated dose; reducing actual contamination through remediation actions; reducing exposure to radionuclides through implementation of land-use restrictions; or some combination of these options.

DandD and RESRAD/RESRAD-BUILD codes provide a sensitivity analysis module that allows the licensee to identify sensitive parameters (e.g., those having the greatest impact on dose assessment results), and to explore potential reductions in the uncertainty associated with those parameters. Note that one option may include elimination of exposure pathways due to site-specific considerations.

Step 9: All of the options identified in Step 8 are analyzed and compared in order to optimize selection of a preferred set of options to go forward with. This options analysis may consider cost of implementation, likelihood of success (and the expected costs associated with success or failure to achieve the desired results when the option is implemented), timing considerations and constraints, and potentially other quantitative and/or qualitative selection criteria. The DandD and RESRAD software allow displaying the potential impact on the dose results through selective truncation of the uncertainty bounds of the input parameters.

Step 10: The activities in Steps 8 and 9 provide information for the licensee to choose the preferred options based on considerations of cost, likelihood of success, timeliness, and other considerations. Based on the results of the DandD and RESRAD/RESRAD-BUILD sensitivity analysis, for example, a licensee may identify one or more parameters that may be modified based on acquisition of site-specific information and data. If new data can reduce the uncertainty associated with sensitive parameters, the licensee may be able to defend a new calculated dose that meets the license termination criteria. If no viable options exist at this time, the licensee may decide to defer actions at this site (Step 13) until circumstances allow re-visiting license termination actions.

Step 11: Under Step 11, the preferred option is implemented. The licensee commits resources to obtain the information necessary to support revisions to the parameters identified in Steps 8 and 9.

Step 12: Once data are successfully obtained, the affected parameters for the pre-defined models are revised as appropriate. Also, data may support elimination of one or more of the exposure pathways in the pre-defined scenarios. DandD and RESRAD/RESRAD-BUILD codes provide very simple and straightforward modification of the pathways and parameters of interest. The software also includes in Help full documentation of the original basis for the parameter distributions, references, and sources of information the reviewer might seek in order to defend modifications based on actual site-specific data and circumstances.

Once the pathways and parameters are revised, the user would re-visit Steps 4 and 5 to determine the impact of the revisions on demonstrating compliance with the performance objectives. If met, the user proceeds to

Steps 6 and 7. If the performance objective is still exceeded, the assessor returns to Steps 8 and 9 to analyze remaining options to proceed.

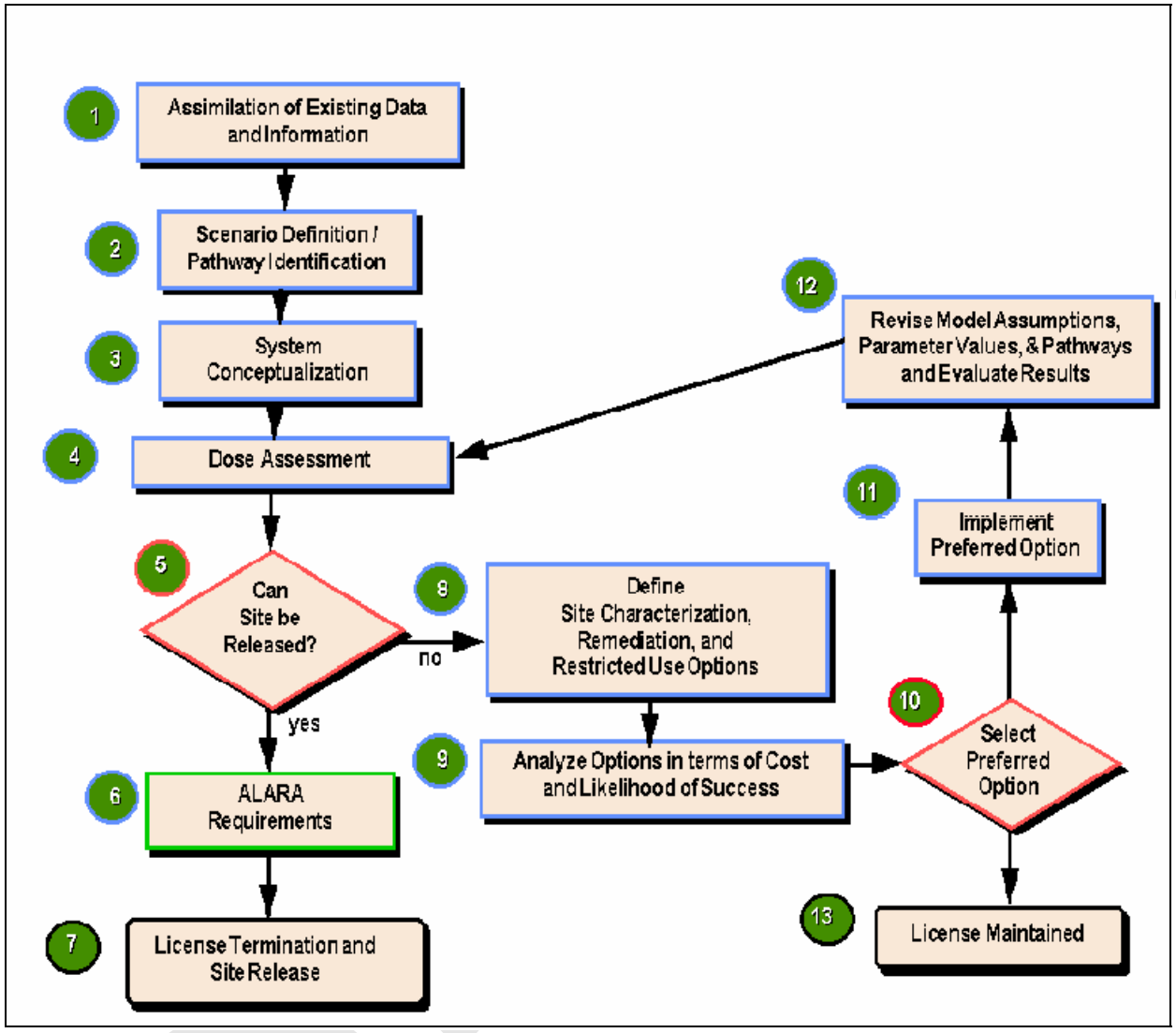

Figure C1.1 Decommissioning and License Termination Framework.

2.0 Criteria for Conducting Screening

2.1 Introduction

This section pertains to staff review of licensee's demonstration of compliance with the dose criteria, in 10 CFR Part 20, Subpart E, using a screening approach dose analysis. Staff review of screening analysis for compliance with the dose criteria should be performed using one or more of the currently available screening tools: (1) a look-up table for common beta-/gamma- emitting radionuclides for building surface contamination (63 FR 64132, Nov. 18, 1998); (2) a look-up table for common radionuclides for soil surface contamination (64 FR 68395, December 7, 1999); and (3) screening levels derived using DandD Version 2.0 for the specific radionuclide(s) and using code default parameters. Other tools for screening analysis might become available in the future depending on staff further development of additional screening tools or look-up tables. Other alternate screening approaches or procedures might be considered based on licensees' request and staff assessment of the merits and level of conservatism of alternate screening approaches or procedures. Screening analysis is usually conducted for simple sites with building surface (e.g., non-volumetric) contamination and/or with surficial soil (approximately 15 cm) of residual radioactivity. Simple and conservative models/codes and parameters, under generic scenarios and default site conditions, are usually employed to define screening derived concentration guideline levels (DCGLs) equivalent to the dose criteria. Due to the conservative nature of the screening analysis approach, the screening DCGLs are expected to be more restrictive than the site-specific DCGLs. Nevertheless, staff should be aware that screening analysis may save licensees time and effort in site characterization, modeling analysis, and reviews that might be needed when selecting a site-specific analysis approach. To conduct a screening analysis review, staff needs to make a generic assessment and evaluation of licensee's justification that the site is indeed qualified for screening. In addition, staff should review the tools (e.g., models, codes, and calculations) and embedded assumptions used in derivation of the screening DCGLs. This section addresses the major issues that reviewers may encounter in the generic screening analysis reviews, and recommendation of approaches for addressing and resolving these issues.

2.2 Issues in Performing Screening Analysis

The major issues associated with the screening analysis that staff may encounter include: (1) the definition of screening and the transition from the screening to the site-specific analysis; (2) qualification of the site for screening, in terms of site physical conditions and compatibility with the code's assumptions and default parameters; and (3) the acceptable screening tools(e.g., code, look-up tables), approaches, and parameters that staff can use to translate the dose (e.g., 25 mrem/y) into equivalent screening concentration levels. Each of these issues are discussed in the following subsections:

2.2.1 Definition of Screening and The Transition from Screening to Site-Specific Analysis:

Staff may encounter some inconsistencies regarding the definition of the term "screening" in dose analysis and therefore the transition from screening to site-specific analysis. These inconsistencies become more apparent specifically when dividing screening approaches into multi-levels (NCRP 1996, 1999). In some cases screening and site-specific terms are mixed and

the term “site-specific screening” is used (Kennedy and Strenge, 1992). In certain cases screening is categorized based on the type of models used (e.g., simple and conservative models vs. more advanced and complex models) and the extent of data and information needed to support the dose analysis. Recommended approaches for resolving this issue are presented in Section 2.3.1.

2.2.2 Qualification of the Site for Screening

Reviewers should be aware that screening analysis, for demonstrate compliance with the dose criteria, under 10 CFR Part 20, Subpart E; may not be applicable for certain site because of the status of contaminants (e.g., location and distribution of radionuclides), or because of certain site-specific physical conditions. Therefore, reviewers need to assess the concerned site regarding existing source-term (e.g., radionuclides distribution) characteristics to ensure consistency with the source-term assumption of the screening model/code used (e.g., DandD). In addition, reviewers should examine specific physical conditions at the concerned site that would invalidate the model and code assumptions associated with the screening code/model. Further, staff should review the selected screening parameters and pathways to ensure that are conservative and consistent with the parameters and pathways of the DandD code designed specifically to over-estimate the dose. Further, staff may determine that there could be conditions at the specific site that cannot be handled by the simple screening model because of the complex nature of the site or because of the simple conceptual model of the DandD screening code. Staff recommended approaches to address and resolve this screening issue are presented in Section 2.3.2.

2.2.3 Screening Tools

It is unclear for certain reviewers what screening tools are acceptable by the NRC. Certain reviewers may believe that using simple common codes (other than DandD) with its deterministic default parameters may be acceptable to derive the desired screening DCGLs. Others may believe that use of any look-up tables published by ceratin scientific committees or authorities might be used directly to convert concentration levels into dose or vice versa for purposes of complying with 10 CFR Part 20, Subpart E. Review staff also raised questions regarding use of the DandD code as a tool for screening, and whether modification of input default parameters is acceptable for screening. The staff has developed approaches and recommendations to address this issue. These approaches and recommendations are presented in Subsection 2.3.3.

2.3 Recommended Approaches

2.3.1 Screening Definition & Approaches for the Transition from Screening to Site-Specific Analysis:

Within the context of the SRP, staff should consider the definition of screening as “the process of developing derived concentration guideline levels (DCGLs) at a site using either NRC’s look-up tables (63 FR 64132, November 18, 1998 ; 64 FR 68395, December 7, 1999) or the latest version (e.g., Version 2.0) of the DandD code developed particularly by the NRC to perform generic screening analysis.” Staff may use the latest version of the DandD code, without modification of the default values, to derive screening values. However, because the currently available DandD

version 1 is overly conservative, and DandD version 2 is under development, staff may use, in the interim, the screening values listed in Tables 5.19 and 6.91 of the NUREG/CR-5512, Volume 3 (Beyeler et al., 1999). Specifically, staff may use Table 5.19 (P_{crit} = 0.90) for the building occupancy screening values and Table 6.91 (P_{crit} = 0.1) for the residential scenario screening values. In addition, when using the DandD code, the screening process would also require use of the default assumptions, scenarios, and default parameters of the DandD code. It should be noted that staff may also develop additional look-up tables for the common alpha-emitters for building surfaces (based on the DandD code and modification of sensitive parameters) or may modify current look-up tables. In addition, staff may also consider possible use of other screening tools (e.g., other look-up tables or other conservative codes/models) through evaluation and comparison of the level of conservatism, compatibilities, and consistencies of these tools with the DandD code default conditions and with site-specific conditions. Staff may evaluate possible use of other screening tools on case-by-case basis. In general, staff should recognize that when users select other approaches or models for the dose analysis, or modify the DandD code default parameters, scenarios, and/or pathways, they would be considered entering into the site-specific analysis mode. Therefore, staff should not categorize screening into different levels because specific criteria for each screening level and dose approaches for a specific screening are difficult to establish.

Review staff should recognize the advantage of selecting a screening approach for demonstrating compliance with the dose criteria because it requires minimum justification, no characterization, and minimum review by the staff. On the other hand, for site-specific analysis, staff would require the licensee to provide justifications and site-specific information, as necessary, to support changes in parameters, or changes of codes/models and default assumptions. Table C2.1 provides a brief summary of attributes and merits of each screening and site-specific analysis approaches.

As noted in Table C2.1, the models, scenarios, and parameters used in screening are intended to be conservative because the lack of information about a site warrants use of rather conservative models and default conditions to ensure that the derived dose is not under-estimated. In other words, at the screening stage of analysis, it is intended to over-estimate the dose to ensure that for 90% of the screening cases the derived dose is not under-estimated. In performing screening analysis, staff should recognize additional significant difference between screening and site-specific analysis which is the basis for selection of the compliance dose regarding treating uncertainties. In the screening analysis, the 90^{th} percentile of the dose distribution is used whereas the peak of the mean dose over time (e.g., 1000 years) or the mean of the peak dose distribution may used in the site-specific analysis. In summary, staff should note that there are two modes of dose modeling analysis, screening and site-specific. As soon as default parameters are changed, source- term conditions are modified, and/or different models/codes are used; any of these situations would indicate a transition from screening to site-specific analysis.

Table C2.1 Attributes of Screening and Site-Specific Analysis.

Attribute	Screening	Site-Specific
Models/Codes	DandD Version 2.0 (Others may be accepted)	Any model/code compatible with the site and approved by staff
Scope of Application	Only for sites qualified for screening	Any site
Parameters	DandD default parameters	Site-specific and/or surrogates with justification
Scenarios/pathways	DandD default scenarios/pathways	Scenarios/pathways may be modified based on site condition
Basis of dose Selection & Uncertainty	The peak dose at the 90th percentile of the peak dose distribution within 1000 years	Peak of the mean annual doses within 1000 years, or mean of the peak dose distribution

2.3.2 Site Qualification for Screening:

When using the screening approach for demonstration of compliance with the dose criteria in 10 CFR Part 20, Subpart E; reviewers need to demonstrate that the particular site conditions (e.g., physical and source-term conditions) are compatible and consistent with the DandD model assumptions (Kennedy and Strenge, 1992). In addition, the default parameters and default scenarios/pathways must also be used in the screening dose analysis. Therefore, reviewers should examine the concerned site conceptual model, the generic source-term characteristics, and other attributes of the sites to ensure that the site is qualified for screening. In this regard, review staff should examine the following aspects of site conditions to qualify for screening:

Building Surface Contamination:

2.1 the contamination on building surfaces (e.g., walls, floors, ceilings) should be surficial and non-volumetric(e.g., #10 mm)

2.2 contamination on surfaces is mostly fixed (not loose) with the fraction of loose contamination not to exceed 10% of the total surface activity

2.3 the screening criteria may not apply to surfaces such as buried structures (e.g., drainage or sewer pipes) or mobile equipment within the building; such structures and buried surfaces will be treated on a case-by-case basis.

Surface Soil Contamination:

a) the initial residual radioactivity (after decommissioning) is contained in the top layer of the surface soil (e.g., 15-30 cm)
b) the unsaturated zone and the groundwater are initially free of contamination
c) the vertical saturated hydraulic conductivity at the specific site is greater than the infiltration rate.

After qualifying the site for screening, reviewers may compare the actual level of contamination at the concerned site with the screening levels published in the NRC's look-up tables or may use the latest version of the DandD code.

Questions were raised regarding qualification for screening analysis of sites with contaminated areas larger than the current default cultivated area (e.g., 2400 m^2). Staff evaluated the effect of a large contaminated area on the derived screening dose. Staff determined that this effect is trivial for sites with the dominant dose arising from direct exposure or inhalation. For sites with significant dose contribution associated with the ingestion pathway (specifically ingestion associated with the drinking water and irrigation pathways); this effect could be appreciable. Staff determined that for sites with a contaminated areas of 6000 - 7200 m^2 the dose may be underestimated under worst conditions by a factor of 2-3. However, the staff analysis showed that if users select the site-specific analysis the dose would be far less than the estimated dose. For sites with areas larger than 7200 m^2, this effect is not appreciable. Therefore, review staff should accept screening analysis relatively large-area sites because they may be counted among the 10 % of the sites where the dose may be slightly underestimated. In addition, because of the conservative assumptions of the DandD code, it is more likely that the derived dose based on use of other codes or use of a site-specific analysis would be far less than the derived dose using these default conditions. In summary, assuming that the site is qualified for screening based on the above listed criteria, the screening approach would be accepted for sites with areas larger than the default cultivated area (i.e., 2400 m^2).

It should be noted that reviewers should also examine certain complex site conditions that may disqualify the site for screening. Examples of such complex site conditions may include: highly fractured formation, karst conditions, extensive surface-water contamination, and/or highly non-homogeneous distribution of contamination. Therefore, reviewers should ensure that the site meet the definition of "simple site" to qualify for screening.

2.3.3 Acceptable Screening Tools:

The currently available screening tools that reviewers should accept directly for screening analysis include:

(1) A look-up table (Table C2.2) for common beta-/gamma- emitting radionuclides for building surface contamination (63 FR 64132, Nov. 18, 1998).
(2) A look-up table (Table C2.3) for common radionuclides for soil surface contamination (64 FR 68395, December 7, 1999).

The screening values in Tables C2.2 and C2.3 are intended for single radionuclides. For radionuclides in mixtures, the "sum of fractions" rule can be used. These values were derived using DandD screening methodology based on selection of the 90th percentile of the output dose distribution for each specific radionuclide (or radionuclide with the specific decay chain). Behavior parameters were set at the mean of the distribution of the assumed critical group. The metabolic parameters were set at the Standard Man or at the mean of the distribution for an average man.

(3) Screening levels derived using DandD Version 2.0 for the specific radionuclide and using code default parameters:.

The staff issued, in August 1998, the DandD version 1.0 code for screening and simple site-specific analysis. Staff and users (through public workshops) have identified several areas where DandD, version 1, may be overly conservative. One such conservatism is the methodology used for establishing a single default parameter set for all radionuclides listed in the DandD code. That is, if the default parameter set was tailored for each specific radionuclide, the dose calculated using DandD model would in most cases be lower. A detailed discussion of the way the default parameters were selected is contained in NUREG/CR-5512, Volume 3 and the conservatism of the DandD code version 1 is discussed in Section 6. Therefore, executing DandD version 1 for deriving the screening DCGL will produce for some radionuclides anomalies due to the artifact in selection of the default parameter set. Staff developed DandD version 2.0 code to minimize this artifact and reduce over-conservatism in the DandD version 1.0 approach. Review staff should use the DandD version 2.0 for screening rather than version 1.0. Similarly, version 2.0 is also more appropriate for site-specific analysis of simple sites. Review staff may access the DandD code at the website: *http: //techconf.llnl.gov*.

(4) Potential use of other tools or approaches for screening:

The current staff position is to limit screening to the look-up tables developed by the NRC and the execution of the latest version of DandD code with the default parameters. As was indicated above staff may develop additional look-up tables or modify the screening tables based on refining of certain sensitive parameters. Further, staff is looking into the possibility of using other simple codes/models for screening such as the probabilistic RESRAD and RESRAD-BUILD codes currently under development. Furthermore, staff may evaluate and examine any request by users for use of other look-up tables developed by specific consensus professional or technical groups or authorities. In this respect, review staff will examine the screening approaches, methodologies, scenarios, and assumptions to ensure compatibility with the current screening methodology using DandD. Further, review staff will also assess site conditions to ensure that screening analysis is appropriate for the concerned sites. In certain cases review staff may need to examine and compare the default screening parameters with their site-specific conditions. The behavior, metabolic, and physical parameters used for screening analysis are listed in Section 7 of the TBD to facilitate this comparison.

Table C2.2 Acceptable License Termination Screening Values of Common Radionuclides for Building Surface Contamination.

Radionuclide	Symbol	Acceptable Screening Levels[1] for Unrestricted Release (dpm/100 cm^2)[2]
Hydrogen-3 (Tritium)	^{3}H	1.2E+08
Carbon-14	^{14}C	3.7E+06
Sodium-22	^{22}Na	9.5E+03
Sulfur -35	^{35}S	1.3E+07
Chlorine-36	^{36}Cl	5.0E+05
Manganese-54	^{54}Mn	3.2E+04
Iron-55	^{55}Fe	4.5E+06
Cobalt-60	^{60}Co	7.1E+03
Nickel-63	^{63}Ni	1.8E+06
Strontium-90	^{90}Sr	8.7E+03
Technetium-99	^{99}Tc	1.3E+06
Iodine-129	^{129}I	3.5E+04
Cesium-137	^{137}Cs	2.8E+04
Iridium-192	^{192}Ir	7.4E+04

[1]Screening levels are based on the assumption that the fraction of removable surface contamination is equal to 0.1. For cases when the fraction of removable contamination is undetermined or higher than 0.1, users may assume, for screening purposes, that 100% of surface contamination is removable; and therefore the screening levels should be decreased by a factor of 10. Alternatively, users having site-specific data on the fraction of removable contamination (e.g., within 10% to 100% range) may calculate site-specific screening levels using DandD Version 1, based on site-specific resuspension factor.

[2]Units are disintegrations per minute per 100 square centimeters (dpm/100 cm^2). 1 dpm is equivalent to 0.0167 becquerel (Bq). The screening values represent surface concentrations of individual radionuclides that would be deemed in compliance with the 0.25 mSv/yr (25 mrem/yr) unrestricted release dose limit in 10 CFR 20.1402. For radionuclides in a mixture, the "sum of fractions" rule applies; see 10 CFR Part 20, Appendix B, Note 4.

Table C2.3 Interim Screening Values[1] (pCi/g) of Common Radionuclides for Soil Surface Contamination Levels.

Radionuclide	Surface Soil Screening Values[2]
H-3	1.1 E+02
C-14	1.2 E+01
Na-22	4.3 E+00
S-35	2.7 E+02
Cl-36	3.6 E-01
Ca-45	5.7 E+01
Sc-46	1.5 E+01
Mn-54	1.5 E+01
Fe-55	1.0 E+04
Co-57	1.5 E+02
Co-60	3.8 E+00
Ni-59	5.5 E+03
Ni-63	2.1 E+03
Sr-90	1.7 E+00
Nb-94	5.8 E+00
Tc-99	1.9 E+01
I-129	5.0 E-01
Cs-134	5.7 E+00
Cs-137	1.1 E+01
Eu-152	8.7 E+00
Eu-154	8.0 E+00
Ir-192	4.1 E+01
Pb-210	9.0 E-01
Ra-226	7.0 E-01
Ra-226 + C[3]	6.0 E-01
Ac-227	5.0 E-01
Ac-227 + C	5.0 E-01

Radionuclide	Surface Soil Screening Values[3]
Th-228	4.7 E+00
Th-228 + C	4.7 E+00
Th-230	1.8 E+00
Th-230 + C	6.0 E-01
Th-232	1.1 E+00
Th-232 + C	1.1 E+00
Pa-231	3.0 E-01
Pa-231 + C	3.0 E-01
U-234	1.3 E+01
U-235	8.0 E+00
U-235 + C	2.9 E-01
U-238	1.4 E+01
U-238 + C	5.0 E-01
Pu-238	2.5 E+00
Pu-239	2.3 E+00
Pu-241	7.2 E+01
Am-241	2.1 E+00
Cm-242	1.6 E+02
Cm-243	3.2 E+00

[1]These values represent superficial surface soil concentrations of individual radionuclides that would be deemed in compliance with the 25 mrem/y (0.25 mSv) unrestricted release dose limit in 10 CFR 20.1402. For radionuclides in a mixture, the "sum of fractions" rule applies; see Part 20, Appendix B, Note 4. Refer to NRC Draft Guidance DG-4006 for further information on application of the values in this table.

[2]Screening values (pCi/g) equivalent to 25 mrem/y derived using DandD screening methodology (SNL Letter Report for NRProject JCN W6227, January 30, 1998). These values were derived based on selection of the 90th Percentile of the output dose distribution for each specific radionuclide (or radionuclide with the specific decay chain). Behavioral parameters are set at the mean of the distribution of the assumed critical group. The Metabolic parameters are set at Standard Man or at the mean of the distribution for an average man.

[3]"+C" indicates a value for a radionuclide with its decay progeny present in equilibrium. The values are concentrations of the parent radionuclide, but account for contributions from the complete chain of progeny in equilibrium with the parent radionuclide.

Section 3. Source-term Abstraction

Section 3.1 Introduction

Source-term abstraction is the process of developing a conceptual representation of the radioactive source material at a site or facility (hereafter referred to collectively as "site"). Typically, the radiological conditions at a site proposed for decommissioning are relatively complex. Source-term abstraction is necessary to allow the detailed radiological characterization of the site to be incorporated into the mathematical and computer models that are used to estimate radiological impacts, such as dose. The abstraction process involves generalizing the radiological characteristics across the site to produce a simplified representation that will facilitate the modeling of radiological impacts. The conceptual representation of the source developed in the abstraction process, however, should not be simplified to the extent that radiological impacts are significantly underestimated or unrealistically overestimated.

As discussed in SRP Module 5, source-term abstraction serves as the starting point for the dose modeling process. The conceptual abstraction of the source term is combined with the physical characteristics of the site and characteristics of the critical group receptor to develop the conceptual model for the site. This conceptual model provides the basis for identifying applicable exposure scenarios, pathways, and selection of computer models. These other elements of dose modeling are discussed in subsequent sections of this document.

SRP Module 4 discusses the information the licensee is expected to provide regarding the existing radiological characterization of the site. The licensee is expected to provide a description of the types, levels and extent of radioactive material contaminated at the site. This will include contamination in all media, including buildings, systems and equipment, surface and subsurface soil, and surface and subsurface groundwater. The source-term abstraction should be based on the characterization of the radiological status reviewed under SRP Module 4 (e.g., process historical development, records of leakage or disposal). The licensee should explicitly relate the information provided in the discussion of radiological status of the site with the discussion of source-term abstraction. The reviewer should be able to clearly interpret the relationship.

Generally, in the source-term abstraction process, the licensee may focus on four specific elements of the source term:

- The licensee should identify the radionuclides of concern. This should be taken directly from the description of the radiological status of the site. The radionuclides should be identified based on pre-remediation radiological status. All radionuclides potentially present at the site should be included, so that their presence or absence may be verified during the final status survey.

- The licensee should describe the physical/chemical form of the contaminated media *anticipated at the time of final status survey and site release*. The licensee should indicate whether the residual contamination will be limited to building surfaces and/or surface soil, or will involve other media, such as subsurface soil, debris or waste materials (e.g., sludge, slag, tailings), or groundwater and surface water.

- The licensee may need to delineate the spatial extent of the residual contamination *anticipated at the time of final status survey and site release*. The delineation of the spatial extent will include a description of areal extent of radionuclides throughout the site and, for soil contamination, the vertical extent of radionuclides below the ground surface. The delineation of spatial extent and depth will establish the source areas and volumes. Depending on the presence of specific radionuclides, source areas and volumes may be radionuclide-specific.

- Finally, the licensee may need to define the distribution of each radionuclide throughout the delineated source areas and volumes *anticipated at the time of final status survey and site release*. The distribution of a radionuclide through the source should be defined in terms of representative volumetric or areal concentrations. In addition, for volumetrically contaminated soil, the licensee may provide an estimate of total radioactivity of each radionuclide.

- The licensee needs to define sources in groundwater or surface water, if any, based on environmental monitoring and sampling of aquifers and surface water bodies. A site with groundwater or surface water contamination may be categorized as "complex" and will require more advanced dose modeling analysis.

In the source-term abstraction process, the licensee will always need to address the first two of these four elements. Whether or not the licensee needs to address the third and fourth elements depends on the objective of the licensee's dose modeling. This is discussed below in Section 3.3.

3.2 Issues Associated With Source-term Abstraction

The level of effort that a licensee expends to develop a conceptualization of a source term should be commensurate with the licensee's approach to demonstrating compliance with the release criterion. Also, the focus should be on the source term characteristics anticipated to exist at the site at the time of final status survey and release, following any planned remediation.

If a licensee plans to utilize the screening derived concentration guidelines (DCGLs) published by the NRC in the Federal Register, a licensee should only have to identify the radionuclides that may be present at the site, and demonstrate that the conditions at the site meet the prerequisites for using the screening values (i.e., residual contamination is limited to building surfaces or the uppermost 15 to 30 cm of surface soil and no contamination of groundwater or surface water). The licensee's source term abstraction would not have to address issues such as existing radiological conditions, areal and volumetric extent of residual contamination, or spatial variability or radiological conditions for such sources. This is discussed further in Section 3.3.

If a licensee anticipates that residual contamination will be limited to building surfaces or surface soils at the time of final status survey, but considers the published DCGLs overly restrictive, the licensee may develop site-specific DCGLs. In this case, the licensee would most likely have to delineate the anticipated areal extent of residual contamination. However, the licensee would not

have to discuss the anticipated spatial variability of radionuclide concentrations within the anticipated area of residual contamination.

A licensee will have to provide a site-specific dose assessment if the contamination the licensee intends to leave at the site is not limited to building contamination or surface soil. In this case, the licensee would have to delineate the spatial extent (laterally and vertically) of the contamination, and would provide a discussion of the spatial variability of the physical, chemical and radiological characteristics of the contaminated media.

Ideally, the source characteristics at a site would be relatively uniform, justifying simplified abstraction. However, this is generally not the case. Issues may arise when the residual contamination projected at a site at the time of release falls short of the ideal case. These issues may include the following:

- Spatial extent
  - limited areal extent of residual contamination
  - irregular areal shape
  - varying depth of contamination in soil

- Spatial variability
  - non-uniform distribution of radioactivity throughout a site
  - limited areas of relatively elevated radionuclide concentrations
  - multiple non-contiguous areas of residual contamination
  - non-uniform physical and chemical characteristics

The following approach to source-term abstraction addresses most of these issues. Others (such as irregular areal shape) are best addressed by appropriate selection of computer codes.

3.3 Approach to Source-term Abstraction

A licensee's approach to source-term abstraction will depend on the objective of the dose modeling presented in the decommissioning plan. Generally, the licensee's dose modeling will have one of the following objectives:

1. Develop derived concentration guideline levels (DCGLs) commensurate with demonstrating compliance with the dose-based release criterion, and then demonstrate through final status survey that residual radioactivity concentrations at the site are below the DCGLs.

2. Assess dose associated with actual concentrations of residual radioactivity distributed across the site to determine whether the concentrations will result in a dose below the regulatory dose criterion.

The first objective is where the licensee intends to demonstrate that, at the time of final status survey prior to release, residual radionuclide concentrations across the site are below a pre-specified concentration limit with some pre-specified degree of confidence. The design of the final

status survey would be based on the proposed DCGLs, in accordance with the *Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM)* (NUREG-1575; NRC, 1997). This approach is limited to building surface and surface soil contamination. The MARSSIM process does not require that the licensee incorporate information regarding the existing (i.e., pre-remediation or pre-final status survey) spatial distribution of radioactivity into the source-term abstraction. The identification of DCGLs may involve site-specific model and parameter assumptions, or may utilize "screening" analyses.

The second objective is where the licensee intends to assess potential radiation doses that may result from specified levels of radioactive material. The licensee may intend to leave various quantities of radioactively contaminated material on the site after release (i.e., residual contamination). The contaminated material may not be limited to building surfaces or surface soils, but may include contaminated subsurface soil, debris and waste. The licensee's dose modeling should demonstrate that the residual contamination should not result in radiation doses in excess of applicable regulatory limits. This modeling would be site specific. Most likely, this modeling objective would require that the licensee incorporate information regarding both the spatial extent and spatial variability of radioactivity into the source-term abstraction.

Table C3.1 summarizes the approach to source-term abstraction that the licensee should adopt depending on the licensee's dose modeling objective and whether the licensee is providing screening or site-specific analyses. This table can serve as an index for the reviewer of the licensee's source-term abstraction. Source-term abstraction, with respect to identifying DCGLs (the first objective), is discussed in Section 3.3.1. Source-term abstraction, with respect to assessing doses from specified levels of radioactive material (the second objection), is discussed in Section 3.3.2.

Table C3.1 Summary of Source-Term Abstraction Approaches Based on Dose-Modeling Objective.

OBJECTIVE:	**Screening**	**Site-Specific**
Identify DCGLs	No source-term abstraction necessary beyond radionuclide identification (Assume unit radionuclide concentrations)	Delineate proposed lateral and vertical extent of residual contamination (Assume unit radionuclide concentrations)
OBJECTIVE: Provide Dose Assessment	Site-specific source-term abstraction incorporating spatial extent and variability	

Section 3.3.1 Dose modeling objective one: Identify DCGLs

The MARSSIM approach, as documented in NUREG-1575, requires that a licensee establish a set of derived concentration guideline levels (DCGLs) prior to conducting a final status survey. In fact, the design of the final status survey will be based on the identified DCGLs. DCGL is defined in MARSSIM as:

> "*a derived, radionuclide-specific activity concentration within a survey unit corresponding to the release criterion....DCGLs are derived from activity/dose relationships through various exposure pathway scenarios.*"

The $DCGL_W$ is the concentration of a radionuclide which, if distributed uniformly across a survey unit, would result in an estimated dose equal to the applicable dose limit. The $DCGL_{EMC}$ is the concentration of a radionuclide which, if distributed uniformly across a smaller limited area within a survey unit, would result in an estimated dose equal to the applicable dose limit.

Two approaches are possible for developing DCGLs: screening and site-specific analysis.

Screening DCGLs The NRC has published radionuclide-specific screening DCGLs in the Federal Register for residual building-surface radioactivity and residual surface-soil radioactivity. The DCGLs in the Federal Register are $DCGL_W$s, in that they are intended to be concentrations which, if distributed uniformly across a building or soil surface, would individually result in a dose equal to the dose criterion. The licensee may adopt these screening DCGLs without additional dose modeling, if the site is suitable for screening analysis (see Section 2). Alternatively, the licensee may use the DandD computer code to develop screening DCGLs. The licensee would use the code to determine the dose attributable to a unit concentration of a radionuclide and scale the result to determine the DCGL for the radionuclide. Either of these methods for identifying screening DCGLs requires only that (1) the licensee identify the radionuclides of concern for the site and (2) the licensee demonstrate that the source term and model screening assumptions are satisfied. Thus, this approach requires essentially no source-term abstraction. The screening process and the source term screening assumptions are discussed in detail in Section 2 of this document.

Prior to designing a final status survey, the licensee will likely need to identify a $DCGL_{EMC}$ for each radionuclide over a range of smaller limited areas. Since the conservative screening models of DandD are not appropriate for modeling small limited areas of contamination, use of the DandD screening code would likely result in $DCGL_{EMC}$ values that are overly conservative. Therefore, licensees will likely use other codes or approaches to develop $DCGL_{EMC}$ values. These would be considered "site-specific" analyses in that they would not be using the DandD code with the default screening values.

Site-Specific DCGLs The licensee may choose to identify site-specific DCGLs if (1) the site conditions are not consistent with screening criteria, or (2) the licensee believes the screening DCGLs are unnecessarily restrictive. (Refer to Section 2 for a discussion of the screening criteria.) As defined in MARSSIM, the site-specific DCGLs will be derived from activity/dose relationships through various exposure pathway scenarios. "Site-specific" in this context may refer to the selection of conceptual models/computer models, physical (site) input parameter values, or behavioral/metabolic input parameter values. These aspects of site-specific analyses are

discussed in other sections of this document. "Site-specific" may also refer to the source-term abstraction.

From the MARSSIM perspective, identifying a site-specific DCGL still begins with assuming a uniform radionuclide concentration across some source area (building surface) or volume (surface soil). The site-specific DCGL for a particular radionuclide will be identified by evaluating the dose resulting from a unit concentration and then scaling the result. Spatial variability of the radionuclide concentration within the area or volume is not evaluated in identifying the DCGLs, but is taken into account in the statistical analysis of the data collected during the final status survey. In identifying the site-specific DCGLs, the licensee may, however, take the spatial extent into account.

If the licensee is certain that the residual radionuclide concentration is limited to a specific lateral extent, the licensee may incorporate the "area of residual contamination" into the identification of DCGLs. This is similar to identifying a $DCGL_{EMC}$, and will generally result in an increased DCGL. If the licensee is using the DandD computer code to model doses, the licensee's approach to this analysis may be similar to the approach for identifying the screening $DCGL_{EMC}$ discussed in the preceding section. Alternatively, other computer modeling codes, such as RESRAD, allow the user to directly specify the area of contamination. Through the final status survey, the licensee would have to demonstrate that the DCGL is satisfied within the specified area of residual contamination, and would have to demonstrate that residual contamination is not present outside the specified area of residual contamination. The licensee would still be required to develop $DCGL_{EMC}$s for smaller areas within the area of residual contamination in order to adequately design the final status survey.

In addition to specifying a limited area of residual contamination in developing the site-specific DCGLs for soil, the licensee should also appropriately represent the vertical extent of residual contamination within the area. The screening DCGLs and the DandD code assume that residual contamination is contained within the uppermost 15 to 30 centimeters of soil. If the licensee intends to leave residual contamination at depths below 15 to 30 centimeters, this should be reflected in the DCGL. Otherwise, leaving residual contamination below 15 to 30 centimeters may not be acceptable.

For subsurface contamination (contamination at depths >15-30 cm.), the reviewer should evaluate whether the licensee has reviewed existing historical site data (including previous processes or practices) and site characterization data to establish an adequate conceptual model of the subsurface source specifically regarding horizontal and vertical extent of contamination. Lateral and vertical trends of variation in concentration for each specific radionuclide should be evaluated. Since certain radionuclides have higher mobility than others, radionuclides ratios may not be maintained as constant across subsurface soil. In other words, radionuclide concentration within the unsaturated zone may vary depending on the original source location and the time since contamination existed. The reviewer should evaluate whether the licensee has reviewed the physical and chemical properties of the source and the surface/subsurface formation to assess potential for leaching or retardation within the natural physical system of the concerned site. In this context, the reviewer should evaluate the selected physical parameters and the physical conceptual model of the site versus actual subsurface geologic units or formation to ensure conservative selection of pertaining sensitive physical parameters. The reviewer should also

consider physical variability in subsurface soil and the unsaturated zone, and the selected depth to water table considering the lower boundary of the subsurface source-term.

If the thickness of residual contamination that the licensee intends to leave at the site is generally uniform across the site, the licensee may choose to use an upper bounding value for modeling the thickness. Alternatively, the licensee may choose to adopt an area-weighted approach to calculate an representative thickness. The representative thickness may be the area-weighted average value, or may reflect a conservative upper-percentile value. The reviewer should ensure that the representative thickness value proposed by the licensee does not significantly underestimate localized thicknesses at sites where the thickness of the proposed residually contaminated soil varies greatly across the site.

If appropriate, the licensee should provide maps and cross-sections detailing the proposed lateral and vertical extent of residual contamination left on the site.

Section 3.3.2 Dose modeling objective two: Assess Dose

An alternative objective that a licensee may have for performing and submitting dose modeling may be to assess doses attributable to specific quantities of radioactive material. While the development of DCGLs focuses on the determination of radionuclide concentrations corresponding to a specified dose, the dose assessment objective focuses on the determination of doses corresponding to specified radionuclide concentrations.

In this situation, the licensee should give much more attention to the source-term abstraction. The licensee should address all four elements of the source-term abstraction:

- identify the radionuclides of concern
- delineate the spatial extent of residual contamination
- represent the spatial variability of residual contamination
- incorporate spatial variability of physical and chemical characteristics of the contaminated media

The licensee should focus on the distribution of radioactive material expected to be present at the time of final status survey and subsequent site release. The licensee may assess doses attributable to existing radiological conditions at the site if the licensee can demonstrate that the existing radiological conditions reasonably bound conditions expected at final status survey, from a dose perspective.

The first two elements of source-term abstraction -- radionuclides of concern and spatial extent -- were considered in the discussion of source-term abstraction for development of DCGLs. Spatial variability was not considered since it is statistically evaluated following final status survey. In dose assessment, however, spatial variability must be factored into the source-term abstraction prior to dose modeling.

Assuming that the licensee has identified the radionuclides of concern and delineated the spatial extent of residual contamination, the licensee should provide a projection of residual radionuclide concentration distribution and total residual radionuclide inventory across the site. This projection should be directly tied to the characterization of existing radiological conditions at the site. The site may then be divided into relatively large areas that are radiological distinct, based on radionuclide concentration or depth of residual contamination. The licensee should statistically demonstrate that the radionuclide concentrations or contamination depth within an area will be relatively uniform, taking into account the spatial distribution of the data. Similarly, within the larger areas, the licensee should statistically delineate relatively small areas of projected elevated radionuclide concentrations or increased contamination depth. (The licensee should discuss reason for leaving the elevated concentrations in place as residual contamination.)

When complete, the licensee's source-term abstraction should define a site divided into relatively large areas of statistically uniform radionuclide concentrations and residual contamination depth. Within these areas may be relatively small areas of elevated concentration or increased depth. Assuming that the physical and chemical conditions across the site are relatively uniform, the licensee may use this source-term abstraction for modeling and proceed with the dose assessment. The following is a suggested approach:

- Consider each relatively large area independently, and initially ignore the relatively small elevated areas within each large area.

- Assess dose based on the properties of a large area, taking the areal extent into account.

- Repeat the dose assessment, but assume essentially infinite areal extent. The specific approach will depend on the computer modeling code utilized. This will quantify the impact of dividing the site into artificial modeling areas.

- Assess dose attributable to each limited area of elevated concentration, assuming no residual contamination exists outside of the limited area. This may then be combined with the dose attributable to the surrounding larger area to assess the impact of leaving the elevated concentrations.

The above discussion does not specifically address the determination of relatively significant large or small areas. This designation will depend on the areal assumptions underlying the computer modeling code utilized. For example, the DandD code considers the area of cultivation to be uniformly contaminated and irrigated. The area of cultivation depends on the cultivation requirements defined by the specific exposure scenario. Conversely, the RESRAD code considers a range of exposure-pathway specific areas: for example, 400 m^2 for soil ingestion, 1,000 m^2 for plant ingestion, and 20,000 m^2 for milk and meat ingestion. Therefore, the licensee should discuss and justify the designation of relatively large and relatively small areas, based on the computer code utilized. However, by providing the additional assessments identified above, where alternative areas are evaluated, the sensitivity of the dose modeling results to the area designation can be determined.

The licensee may also have to consider the impact of multiple areas of elevated concentration within a single larger area. In general, modeling two small areas independently and combining the results of the two dose assessments will result in a higher dose than if the two areas were combined and modeled as a single area. The higher dose is unrealistic in that it assumes that the receptor location relative to each contaminated area is such that dose is maximized from each contaminated area independently. For a more reasonable estimate of potential dose, these smaller areas may be combined into a single larger area if the concentrations within the smaller areas are comparable. If not, the licensee may model each smaller area individually, and conservatively combine the results.

4.0 Criteria for Selecting and Modifying Scenarios, Pathways, and Critical Groups

4.1 Introduction

After the source term has been evaluated, the question becomes: "How could humans be exposed either directly or indirectly to residual radioactivity?" or "What is the appropriate exposure scenario?" Each exposure scenario must address the following questions:

- How does the residual radioactivity move through the environment?
- Where can humans be exposed to the environmental concentrations?
- What are the exposure group's habits that will determine exposure? (e.g., what do they eat and where does it come from? How much? Where do they get water and how much? How much time do they spend on various activities? etc.)

The ultimate goal of dose modeling is to estimate the dose to a specific receptor. Broad generalizations of the direct or indirect interaction of the affected receptors with the residual radioactivity can be identified for ease of discussion between the licensee, regulator, public and other interested parties. Scenarios are defined as reasonable sets of human activities related to the future use of the site. Therefore, scenarios provide a description of future land uses, human activities and behavior of the natural system.

In most situations, there are numerous possible scenarios of how future human exposure groups could interact with residual radioactivity. The compliance criteria in 10 CFR Part 20 for decommissioning does not require an investigation of all (or many) possible scenarios; its focus is on the dose to members of the critical group. The critical group is defined (at 10 CFR 20.1003) as "the group of individuals reasonably expected to receive the greatest exposure to residual radioactivity for any applicable set of circumstances."

By combining knowledge about the answers to (1) and (2) the analyst can develop exposure pathways. Exposure pathways are the routes that residual radioactivity travels through the environment from its source until it interacts with a human. They can be fairly simple (e.g., surface soil residual radioactivity emits gamma radiation which results in direct exposure to the individual standing on the soil) or they can be fairly involved (e.g., the residual radioactivity in the surface soil leaches through the unsaturated soil layers into the underlying aquifer and the water from the aquifer is pumped out by the exposed individual for use as drinking water, which results in the exposed individual ingesting the environmental concentrations). Exposure pathways typically fall into three principal categories identified by the manner in which the exposed individual interacts with the environmental concentrations resulting from the residual radioactivity: ingestion, inhalation, or external (i.e., direct) exposure pathways.

As required under 10 CFR Part 20, Subpart E, the dose from residual radioactivity is evaluated for the average member of the critical group, which is not necessarily the same as the maximally exposed individual. This is not a reduction in the level of protection provided to the public, but an attempt to emphasize the uncertainty and assumptions needed in calculating potential future doses, while limiting boundless speculation on possible future exposure scenarios. While it is

possible to actually identify with confidence the most exposed member of the public in some operational situations (through monitoring, time-studies, distance from the facility, etc.), identification of the specific individual who will receive the highest dose some time (up to 1000 years) in the future is impractical, if not impossible. Speculation on his or her habits, characteristics, age, or metabolism could be endless. The use of the "average member of the critical group" acknowledges that any hypothetical "individual" used in the performance assessment is based, in some manner, on the statistical results from data sets (e.g., the breathing rate is based on the range of possible breathing rates) gathered from groups of individuals. While bounding assumptions could be used to select values for each of the parameters (i.e., the maximum amount of meat, milk, vegetables, possible exposure time, etc.), the result could be an extremely conservative calculation of an unrealistic scenario and may lead to excessively low allowable residual radioactivity levels.

Calculating the dose to the critical group is intended to bound the individual dose to other possible exposure groups because the critical group is a relatively small group of individuals, due to their habits, actions, and characteristics, who could receive among the highest potential dose at some time in the future. By using the hypothetical critical group as the dose receptor, coupled with prudently conservative models, it is highly unlikely that any individual would actually receive doses in excess of that calculated for the average member of the critical group. The description of a critical group's habits, actions, and characteristics should be based on credible assumptions and the information or data ranges used to support the assumptions should be limited in scope to reduce the possibility of adding members of less exposed groups to the critical group.

4.2 Issues in Selecting and Modifying Scenarios, Pathways and Critical Groups

The definition of scenarios, identification of a critical group with its associated exposure pathways, and the dose assessment based on that definition can be generic or site specific. Licensees might:

1. Use screening scenarios, screening groups, and pathway parameters as described in NUREG-1549 (NRC, 1998a) and NUREG/CR-5512, Volume 1 (Kennedy and Strenge, 1992). This can be used for either screening or site specific analyses.
2. Use the default screening scenarios as a starting point to develop more site-specific pathway analyses or critical group habits.
3. Develop site-specific scenarios, critical groups and identify associated exposure pathways from scratch.

To establish either site-specific scenarios, critical groups, and/or sets of exposure pathways, the licensee will need to provide justifications defending its selections. For some licensees, this may require minimum amounts of site-specific data to support the assumptions inherent in the existing default screening scenarios or for removing specific exposure pathways. For others, the licensee may need to thoroughly investigate and justify the appropriateness of the selected scenarios and/or critical groups, which may include evaluation of alternate scenarios and/or critical groups. If a licensee creates the exposure scenario and associated critical group from scratch (e.g., at a site that is grossly different than the assumptions inherent in the default scenarios), the licensee should provide documentation that provides a transparent and traceable audit trail for each of the

assumptions used in developing the exposure scenario and critical group (e.g., justify the inclusion (or exclusion) of a particular exposure pathway).

4.3 Recommended Approach

4.3.1 Screening Analyses

In the case of screening, the decisions involved in identifying the appropriate scenario and critical group with its corresponding exposure pathways has already been done. Scenario descriptions acceptable to NRC for use in the generic screening are developed and contained in the NUREG/CR-5512, Volume 1. NUREG/CR-5512, Vol. 1, and NUREG-1549 provide the rationale for applicability of the generic scenarios, critical groups, and pathways at a site; the rationale and assumptions for scenarios and pathways included (and excluded); and the associated parameter values or ranges. A summary of the scenarios is in Table C4.1 and in Section 7. The latest version of the DandD computer code should contain the latest default data values for the critical group's habits and characteristics.

Building Occupancy Scenario

This scenario accounts for exposure to fixed and removable residual radioactivity on the walls, floor, and ceiling of a decommissioned facility. It assumes that the building will be used for commercial or light industrial activities (e.g., an office building or warehouse).

Pathways include:
External exposure from building surfaces;
Inhalation of (re)suspended removable residual radioactivity; and
Inadvertent ingestion of removable residual radioactivity.

Resident Farmer Scenario

This scenario accounts for exposure involving residual radioactivity that is initially in the surficial soil. A farmer moves onto the site and grows some of his or her diet and uses water tapped from the aquifer under the site.

Pathways include:
External exposure from soil;
Inhalation to (re)suspended soil;
Ingestion of soil;
Ingestion of drinking water from aquifer;
Ingestion of plant products grown in contaminated soil and using aquifer to supply irrigation needs;
Ingestion of animal products grown onsite (using feed and water derived from potentially contaminated sources); and
Ingestion of fish from a pond filled with water from the aquifer.

Table C4.1 Pathways for Generic Scenarios.

4.3.2 Site-Specific Analyses[1]

Site-specific analyses can utilize the generic screening scenario(s) with a little justification. The licensee will need to justify that the site contains no physical features or locations of residual radioactivity other than those assumed in the screening analyses that would invalidate the assumptions made in developing the scenarios. The reviewer should evaluate the justification to provide reasonable assurance that the default scenario would still be appropriate for the site. A site can fail to meet the requirements of the conceptual model (see Section 5.3.1) without invalidating the default scenario, and situations can arise where the default

[1] In this section, unless specifically noted, the use of the word "scenario" includes the critical group definition and associated exposure pathways.

scenario is no longer the limiting case. For example, the site may have pre-existing groundwater contamination, which is counter to the assumptions in the conceptual model inherent in the screening models (see Section 5.3.1), but this may not require any change in the exposure scenario because the residential farmer scenario will still be an appropriate scenario as it contains all of the appropriate exposure pathways including groundwater use for drinking, irrigation, and for animals. Alternately, if the residual radioactivity was a volumetric source in the walls of a building, rather than on the building surfaces, the default exposure scenario of an office worker may not be the scenario leading to the critical group. For certain sets of radionuclides, a building renovation scenario may be more limiting because of the exposure to airborne concentration of material as the walls are modified.

Site-specific scenarios, critical groups, and pathways can be developed and would occur in cases where, for example:

1) major pathways (e.g., the groundwater pathway, or agricultural pathways) associated with the default screening scenarios could be eliminated, either because of physical reasons or site use reasons,
2) the location of the residual radioactivity and the physical features of the site are outside the major assumptions defining the critical group and/or scenarios, and
3) restricted use was proposed for a site.

The second situation listed above can be ambiguous, as a number of assumptions key to the development of the DandD screening tool do not affect the scenario description, and will require a reviewer to evaluate whether the initial default scenario would still be appropriate for the site.

Modifying scenarios or developing a site-specific critical group requires information regarding plausible uses of the site and demographic information. Such information might include considerations of the prevailing (and future) uses of the land and physical characteristics of the site which may constrain site use. It may be necessary to evaluate several potential critical groups, based on different combinations of site-specific scenarios developed from expected pathways and demographics, to determine the group receiving the highest exposure.

For restricted release, similar considerations apply. When analyzing the dose under restricted conditions, the nature of the critical group is likely to change due to site restrictions and institutional controls, which can restrict certain kinds of activities and/or land or water uses, in combination with the physical features of the site. The detailed definition of the scenarios considered for restricted release need to include the impact of the control provisions on the location and behavior of the average member of the appropriate critical group. Restricted release license termination plans must also evaluate the impact if the restrictions were to fail. This may require the licensee to explore different “failure” exposure scenarios, including partial failure of engineered features of the site (e.g., engineered covers, subsurface engineered features whose partial failure may result in focused flow) and, more commonly, use of the site assuming a situation similar to unrestricted release.

The reviewer should evaluate the justifications provided by the licensee on its scenarios using the following appropriate guidance. The guidance is characterized by the general approach used in

development of the scenarios: (1) modifying existing generic exposure scenarios, or (2) developing site-specific scenarios from "scratch."

4.3.2.1 Modification of Generic Scenarios

First, the reviewer should evaluate whether the generic scenario was applicable to the site before modification (see 4.3.1 and the start of 4.3.2). If the scenario was applicable before the licensee started modifying the scenario based on physical features or restrictions, go to the next step and evaluate the justifications for the various modifications performed by the licensee. If the scenario was not initially applicable, that does not mean that final modified scenario is inappropriate for the site conditions. It just means that the review may be more complex than a simple modification of a scenario and the reviewer should evaluate whether it may be more appropriate to evaluate the scenario using the guidance in 4.3.2.2.

The reviewer should identify the modifications done by the licensee to the scenario and evaluate the licensee's justification for those changes. Table C4.2 lists some common exposure scenarios but is by no means comprehensive. The Sandia Letter Report, *Process for Developing Alternate Scenarios at NRC Sites Involved in D&D and License Termination* (Thomas et al., 2000) provides a series of flow charts and sources of information to assist a licensee or reviewer in modifying the default scenarios using site-specific information. See 4.3.3 below for specific guidance on acceptable justifications using of different types of site-specific information, which was adapted from Chapter 6 of the letter report. Additionally, if the licensee's intent is restricted release, the final scenario should be reviewed looking at the effect of site restrictions. The licensee's justifications should support, based on either site restrictions or site-specific data, the elimination of scenarios and/or pathways from the analysis. The reviewer should focus the review on the pathways, and models associated with those pathways, that have the highest likelihood of significant exposures to the critical group.

The licensee may need to evaluate whether the final modified scenario is still the limiting reasonable representation of the critical group

General Scenario Classifications

Building occupancy (Generic screening - NUREG/CR-5512 based).

Residential farmer (Generic screening - NUREG/CR-5512 based).

Urban construction (contaminated soil, no suburban or agricultural uses).This scenario is meant for small urban sites cleared of all original buildings; only contaminated land and/or buried waste remains.

Residential (a more restricted subset of the residential farmer scenario, for those urban or suburban sites where farming is not a realistic projected future use of the site).

Recreational (where the site is preserved for recreational uses only).

Hybrid industrial building occupancy (adds contaminated soil, building may or may not be contaminated).

Drinking water (no on-site use of groundwater; off-site impacts from the contaminated plume).

Table C4.2 Potential Scenarios for use in Dose Assessments.

at the site. This may involve investigation of exposure pathways not covered in the default scenarios.

4.3.2.2 Development of Alternate Scenarios

In some decommissioning cases, either the location of the residual radioactivity, the physical characteristics of the site, and/or planned institutional restrictions may make the default scenarios inappropriate. Development (and review) of alternate scenarios may involve iterative steps involving the development of the conceptual model of the site. For example, the licensee may (1) develop a generic list of exposure pathways, (2) develop the site conceptual model to screen the generic list, (3) the remaining exposure pathways could be aggregated or reduced to the major exposure pathways, and (4) re-evaluate the conceptual model to verify that all the necessary processes are included.

A brief summary of the NRC-recommended pathway analysis process follows.

- The licensee compiles a list of exposure pathways applicable to any contaminated site. There are a number of existing sources of information that can be used. One source is NUREG/CR-5512 (Kennedy and Strenge, 1992) and the list is summarized in Appendix C.1 of NUREG-1549 (NRC, 1998a). Another source, although the guidance is more focused on off-site exposures, is NUREG/CR-5453, Volumes 1 and 2, *Background Information for the Development of a Low-Level Waste Performance Assessment Methodology* (Shipers, 1989; Shipers and Harlan, 1989). Another potential source is the international Features, Events and Processes list which is an expansive generic list that does not strictly deal with decommissioning issues (BIOMOVS II, 1996).

- Categorize the general types of contamination at the site (e.g. sediment or soil, deposits in buildings, surface contamination, surface waters, groundwater, industrial products such as slag).

- Screen out pathways for each contaminant type that do not apply to the site.

- Identify the physical processes pertinent to the pathways for the site.

- Separate the list of exposure pathways into unique pairs of exposure media (e.g. source to groundwater, groundwater to surface water, etc.). Determine the physical processes that are relevant for each exposure media pair and combine the processes with the pathway links.

- Reassemble exposure pathways for each source type, using the exposure media pairs as building blocks, thus associating all the physical processes identified with the individual pairs with the complete pathway.

The licensee's documentation of the decisions made regarding inclusion (or exclusion) of the various pathways should be transparent and traceable. An international working group of Biospheric Model Validation Study, Phase II (BIOMOVS II), established a methodology for developing models to analyze radionuclide behavior in the biosphere and associated radiological exposure pathways (i.e., Reference Biospheres Methodology). BIOMOVS II published the methodology in its Technical Report No.6, *Development of a Reference Biospheres Methodology for Radioactive Waste Disposal* (BIOMOVS II, 1996), and it may be useful as a guide for additional information on a logical method to complete the pathway analysis sets above and include proper justification. Generally, the Reference Biospheres Methodology is more useful for complex sites that may have numerous physical processes that interact in such as a way that a number of different exposure groups may need to be investigated to discover the critical group. Additional work has been done on providing guidance by a working group of the International Atomic Energy Agency's Biosphere Modeling and Assessment (BIOMASS) program (BIOMASS, 1999). Specifically, IAEA Working Document BIOMASS/T1/WD03, *Guidance on the Definition of Critical and Other Hypothetical Exposed Groups for Solid Radioactive Waste Disposal* (BIOMASS, 1999a), may provide additional information on developing a site-specific critical group for situations where the default critical group is inappropriate.

4.3.3 Guidance on Specific Issues

4.3.3.1 Land Use

A licensee's justifications for changes in scenarios or exposure pathways based on local land use practices should focus on current practice in the region. The region of concern can be as large as a 80 km (50 mile) radius. To narrow the focus of current land practices, the licensees can use information on how land use has been changing in the region and more weight should be given to land use practices either close to the site or in similar physical settings. This can be very important for semi-rural sites that are being encroached by suburban residential development. Reviewers may wish to involve discussions with State and local land use planning agencies, if the licensee has not already requested their involvement.

One important consideration of land use arguments is the reliance on State or local codes in building development or well development. In general, for sites looking for unrestricted release, should not rely solely on these arguments as reason to remove pathways or change the scenario unless either the radionuclides have a relatively short-half life (approximately 10 years or less) or the dose from long-lived radionuclides reaches its peak before 100 years.

4.3.3.2 Waterborne Exposure Pathways

Removal of waterborne exposure pathways can range from being global (e.g., all groundwater pathways) to being specific (e.g., no drinking water but still have agricultural/fish pond use). Acceptable justifications are generally based on physical conditions at the site rather than local codes (see 4.3.3.1). Justification of water quality and quantity of the saturated zone should be based on the classification systems used by the U.S. Environmental Protection Agency or the State, as appropriate. Arguments involving depth to water table, or well production capacity,

should have supporting documentation from either the U.S. Geological Survey, appropriate State agency, or an independent consultant.

Reviewers should evaluate the reasons for the classification. The Sandia Letter Report, *Process for Developing Alternate Scenarios at NRC Sites Involved in D&D and License Termination* (Thomas et al., 2000) provides a number of tables in Chapter 6 detailing water quality standards. For example, where the aquifer is classified as not being a source of drinking water but is adequate for stock watering and irrigation, the licensee can eliminate the drinking water pathway but should still maintain the irrigation and meat/milk pathways. Aquifers may exceed certain constituents and still be able to be used for various purposes because those constituents may easily be treatable (e.g., turbidity). In cases where the water may be treatable or because the degree of connection between the aquifer and surface water may make the use of the aquifer questionable, the reviewer should involve the U.S. Environmental Protection Agency and/or the State, as appropriate, in discussions on reasonable assumptions for the aquifer use.

4.3.3.3 Agricultural Pathways

Agricultural pathways may be removed or modified for various reasons: (1) land use patterns (see 4.3.3.1), (2) poor quality soil, (3) topography, and (4) size of contaminated area (see 4.3.3.5). Many justifications will result in the modification of the pathways rather than the complete elimination. For example, the soil may of inappropriate quality to support intensive farming activities but residential gardening may still be reasonable.

Licensees using poor quality soil as a justification for modifying the agricultural pathways should provide the reviewer with supporting documentation from the Soil Conservation Service (SCS), appropriate State or local agency, or an independent consultant. Reviewers should carefully consider whether the state of the soil would reasonably preclude all activities (e.g., due to high salinity of soil) or only certain activities. In most cases, soil quality can reasonably preclude activities such as intensive farming but could allow grazing or small gardens.

When reviewing justifications involving topography, the reviewer should limit speculation of future topographical changes due to civil engineering projects. The reviewer should evaluate the reasonableness of the critical group performing its activities on the current topography, for example, a slope. Supporting documentation should be provided by the licensee in the form of pictures, USGS or similar topographic maps, hand-drawn maps, or a detailed description of how the topography would limit farming. Reviewers may wish to perform a site visit to evaluate the topography firsthand.

4.3.3.4 Age-Dependent Critical Groups

When calculating for compliance with the requirements of Subpart E of 10 CFR Part 20, the intake-to-dose conversion factors used to calculate internal exposures can be found in Federal Guidance Report No. 11 (EPA, 1988), which are based primarily on adults. As stated in the Environmental Protection Agency's Federal Register Notice (59 FR 66414, Dec. 23, 1994) on Federal Radiation Protection Draft Guidance for Exposure of the General Public, which proposes a public dose limit of 1 mSv (100 mrem) per year from all sources:

> These dose conversion factors are appropriate for application to any population adequately characterized by the set of values for physiological parameters developed by the [International Committee on Radiological Protection] and collectively known as "Reference Man." The actual dose to a particular individual from a given intake is dependent upon age and sex, as well as other characteristics. As noted earlier, implementing limits for the general public expressed as age and sex dependent would be difficult...More importantly, the variability in dose due to these factors is comparable in magnitude to the uncertainty in our estimates of the risks which provide the basis for our choice of the [public dose limit]. For this reason EPA believes that, for the purpose of providing radiation protection under the conditions addressed by these recommendations, the assumptions exemplified by Reference Man adequately characterize the general public, and a detailed consideration of age and sex is not generally necessary. (59 *FR* 66423, Dec. 23, 1994)

Since age-based dose conversion factors are not being used, all individuals are assumed to have the same dose conversion factors. Because of this, only in very rare scenarios (generally, single exposure pathway scenarios) will a non-adult individual intake more radionuclides, thereby resulting in a higher dose, than an adult in a similar exposure scenario. One example is the milk pathway, generally, children drink more milk annually than adults. If milk was the only pathway that would expose the individual to a dose, then the child will have a slightly higher dose than the adult. But in most situations, especially ones involving multiple pathways, the total intake of the adult is greater than that of a child. Therefore, the average member of the critical group should be assumed to be an adult and use the proper habits and characteristics of an adult.

4.3.3.5 Area Factors

The extent of residual radioactivity can be taken into account when modifying the default scenarios. The default scenarios assume large areas of homogeneous surface contamination. If the area of residual radioactivity is smaller than the defaults (e.g., 2400 m^2 for DandD), the licensee may propose modifying the exposure pathways to account effect on the critical group's activities. Two methods can be followed: (1) the licensee can reduce the calculated dose by the fraction of the default area or modify usage parameters accordingly, or (2) modify the exposure scenario and pathways to account for the size of the residual radioactivity. When the extent of residual radioactivity becomes smaller, some of the activities are no longer viable as reasonable assumptions for exposure. Generally, the first pathways affected are animal husbandry activities because of the larger area needs for grazing and growing fodder. As a general rule, as the area gets smaller the more the scenario transforms into a residential gardener scenario, so long as the initial residual radioactivity begins in the surface soil. For cases where the residual radioactivity is not in the surficial soil, the original area of contamination may not be as important in scenario development, because some of the primary transport mechanisms result in redistribution of the radionuclides over larger areas (i.e., groundwater used as irrigation).

4.4 Generic Examples

The following examples are provided as situations where the default pathways may be removed or modified.

4.4.1 Removal of Groundwater Pathways

A licensee has extensive contamination of the upper soil horizon and the upper aquifer, which is unconsolidated and the licensee wishes to remove the groundwater pathway because the upper aquifer would not be used as a water source. The aquifer shows relatively high levels of microbial activity, turbidity, and nitrates. In addition, adjacent to the site is a small patch of wetlands that show a great deal of communication with the upper aquifer. The potential yield rate of the upper aquifer is sufficient for domestic use but there is a better quality, confined aquifer, whose horizon is at a depth of approximately 30 m (98.4 ft). In this case, it is questionable that the upper aquifer would actually be used. While it may be possible for someone to treat the contaminants and use the aquifer, there are better sources of water easily available. After consultation with the U.S. Environmental Protection Agency and the State, it is agreed that it would be unreasonable to assume someone would use the upper aquifer as a water source. Therefore, the licensee is allowed to remove the groundwater pathway from the scenario.

4.4.2 Scenario Development for Buried Residual Radioactivity

A site has residual radioactivity buried at a few feet below the surface and the licensee is requesting unrestricted release. The residual radioactivity does not have enough highly energetic gamma-emitters to result in an external dose in the current configuration. Two exposure scenarios can be developed (without any other site-specific information): (1) leaching of the radionuclides to the groundwater which is then used by a residential farmer, and (2) inadvertent intrusion into the buried residual radioactivity by house construction for a resident farmer with the displaced soil, which includes part of the residual radioactivity, spread across the surface. Exposure scenario 2 encompasses all of the exposure pathways and while not all of the source term is in the original position, leaching will occur both from the remaining buried residual radioactivity and the surface soil. Except for cases where an additional 0.6 m (2 ft) of unsaturated zone will make a tremendous difference in travel time to the aquifer, the groundwater concentrations should be similar and therefore, analysis of exposure scenario 2 appears to be the appropriate scenario for the critical group exposure.

At another site, the licensee is requesting unrestricted release of its site. It is removing the buildings but is evaluating the need to remove the concrete pads which has imbedded piping that contains the residual radioactivity. Two scenarios can be reasonably envisioned. The first scenario involves a resident farmer onsite. The farmer builds a house on the concrete pad, without disturbing the imbedded piping. Possible exposure pathways would be external dose from the piping and exposure to leached materials from the piping through groundwater use (e.g., drinking, irrigation, etc.). The second is similar to the building renovation scenario, where the concrete pad and piping is removed from the site. Both should be investigated by the licensee to find the limiting scenario.

4.4.3 Scenario Development for Restricted Release

The site restrictions planned for an alternate site include a restriction, for this example on the deed, on the use of the property for only parkland and an engineered cover is placed over the residual radioactivity. The engineered cover is contoured for use as parkland with a vegetative cover (i.e, not a mound covered in rip-rap). Two scenarios are easily envisioned for the restricted release analysis. The first is recreational use of the property as a city park or golf course, with exposure

scenarios being limited to possible external exposure. The second would involve offsite use of groundwater that contains radionuclides leached from the buried residual radioactivity. The offsite user would be, as a default, a resident farmer utilizing the groundwater for all of their water needs.

The unrestricted case would involve the removal of the institutional control (i.e., the deed restriction) and failure of the engineered cover. Again, two main scenarios can be envisioned.

The first scenario is similar to the default exposure and would involve a residential farmer that uses groundwater from the aquifer under the site. The engineered cover will have been compromised by the placement of the buildings but the cover may still work in some degraded function (e.g., the water infiltration rate would increase from the design rate to some higher rate but probably not as high as the infiltration rate would have been if the cover had never been constructed). Whether buried residual radioactivity had been transported to the surface by construction of the basement of the resident farmer's house would depend on the thickness of the engineered cover. If typical basement depth was deeper than the engineered cover's thickness, some portion of residual radioactivity would be transported to the surface, mixed with the 'clean' cover material, and spread over the site.

The second scenario would involve possible erosion of the cover and subsequently exposure of an onsite resident to the buried radionuclides or radionuclides redistributed by surface water. the exposure scenario would still be a resident farmer. The reasonableness of this scenario would depend on the thickness and erosion-resistence of the engineered cover.

5.0 Criteria to Establish Conceptual Models

5.1 Introduction

Analyzing the release and migration of radionuclides through the natural environment and/or engineered systems, at a specific site, requires the analyst to interpret the nature and features of the site so that the site can be represented by mathematical equations (i.e., mathematical models). This simplified representation of the site, including the associated mathematical models is commonly referred to as the conceptual model of the site.

Figure C5.1 depicts the process of conceptual model development. In dose assessments, developing a conceptual model involves making an abstraction of site data into a form that is capable of being modeled. This development will generally involve making simplifying assumptions, including simplification of the appropriate governing equations, to reflect the physical setting. These simplifying assumptions are usually made in describing the geometry of the system, spatial and temporal variability of parameters, isotropy of the system, and the influence of the surrounding. The conceptual model should provide an illustration or description of site conditions which show or explain contaminant distributions, release mechanisms, exposure pathways and migration routes, and potential receptors. In other words, the conceptual model should explain or illustrate how radionuclides enter, move through, and/or are retained in, and leave the environment.

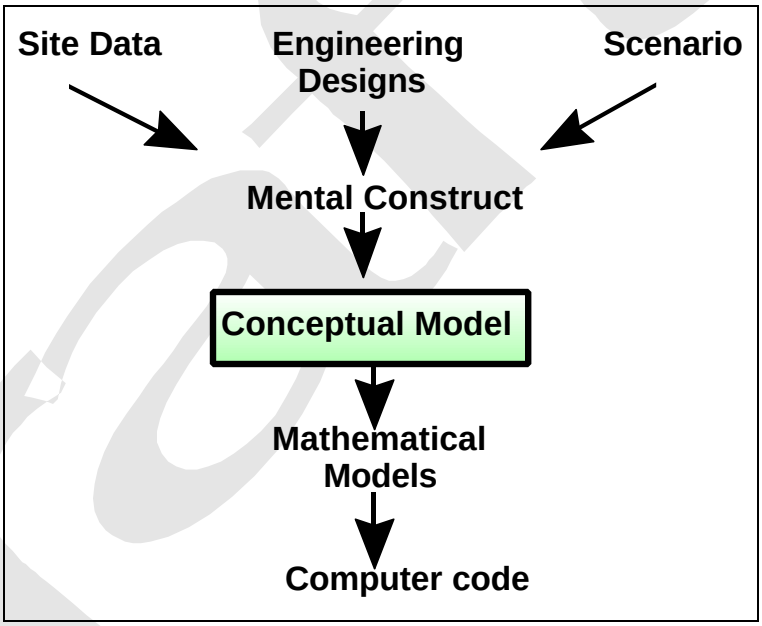

Figure C5.1 Conceptual model development.

As shown in Figure C5.2, developing a conceptual model at a site is Step 3 of the Decommissioning Decision Framework documented in NUREG-1549. Conceptual model development follows after assimilation of site data (Step 1) and definition of scenarios (Step 2) because information from these two steps feeds into its development. In other words, the conceptual model should be based upon what is known about the site from data and information gathered as part of Step 1 and how the site evolves during the period covered by the analysis based upon the assumed land-use scenario defined under Step 2.

Mathematical models are a quantitative representation of the conceptual model. Because the conceptual model provides the linkage between site conditions and features (Steps 1 and 2) and

the computer code(s) (with its associated mathematical models) used in the dose analysis (Step 4 of the Decommissioning Framework), it is a key step in a dose assessment and should not be taken lightly.

5.2 Issues

Uncertainties in conceptual models can be large, and possibly even larger than uncertainties in parameters used in the analysis (James and Oldenburg, 1997). Thus, conceptual model uncertainties can be a significant source of uncertainty in the overall dose assessment. Uncertainties in the conceptual model(s) are generally due to incomplete knowledge about the natural system being analyzed and differing views about how to interpret data representing the system.

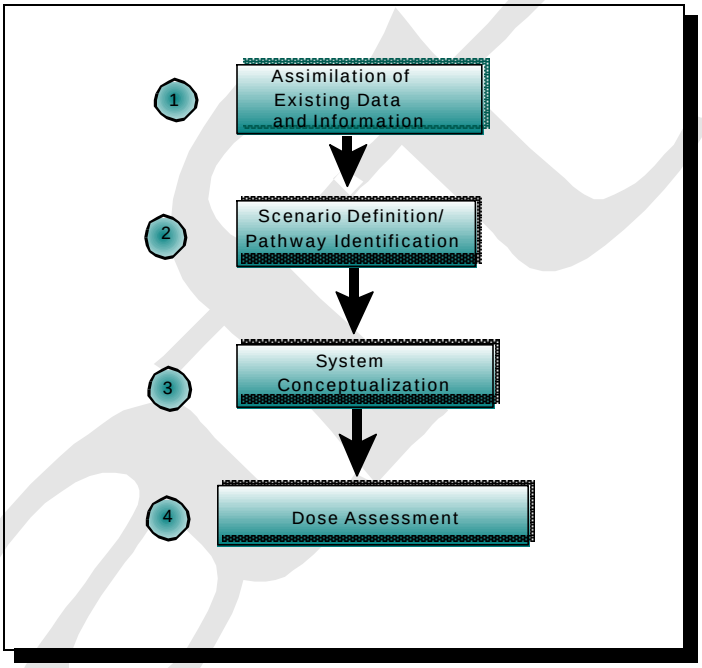

Figure C5.2 Decommissioning Decision Framework

Development of conceptual models is a subjective process based on interpretation of limited (or in most cases, sparse) site data. From these limited data we must determine the key processes and features at the site and how they are likely to affect the movement of radionuclides through the environment. Because our construct of the site is based upon incomplete information, it is possible that multiple interpretations of the same data can be derived. An analyst must also determine the appropriate level of simplification acceptable for representing the site. An overly simplified conceptual model may leave out key site features or conditions that are important in estimating where radionuclides are likely to be transported (thus, where people might be exposed) and when they might get there (thus, the radionuclide concentration when it arrives). On the other hand, an overly complex conceptual model may introduce unnecessary uncertainty and costs into the analyses. As a broad example, simple models contained in screening codes may oversimplify features and processes at a specific site. The analyst also needs to ensure that the appropriate level of detail is provided in the conceptual model. It is important that the conceptual model have sufficient detail and scope for a license reviewer to be able to assess the appropriateness of the computer codes used in the analysis and the defensibility of the assumptions made. In summary, key issues in developing and presenting the conceptual model are identifying the important site features and processes that need to be included in the conceptual model, deciding among possible competing interpretations of the site data, and determining the level of detail needed to describe those features and processes.

5.3 Recommended Approach

5.3.1 Screening

An acceptable dose assessment analysis need not incorporate all the physical, chemical, and biological processes at the site. The scope of the analysis and accordingly the level of sophistication needed in the conceptual model should be based upon the overall objective of the analysis. A performance assessment conceptual model can be simple if it still provides satisfactory confidence in site performance. For an initial screening analysis, little may be known about the site from which to develop a conceptual model. Computer codes used for screening analyses are generally intended to provide a generic and conservative representation of processes and conditions expected for a wide array of sites. Accordingly, the generic conceptual model in such codes may not provide a close representation of conditions and processes at a specific site. Such a generic representation is still acceptable as long as it provides a conservative assessment of the performance of the site.

The DandD code has two default land-use scenarios; a building occupancy and a resident farmer scenario. The building occupancy scenario is intended to account for exposure to both fixed and removable residual radioactive contamination within a building. Exposure pathways included in the building occupancy scenario include external exposure to penetrating radiation, inhalation of resuspended surface contamination, and inadvertent ingestion of surface contamination. The resident farmer scenario is intended to account for exposure to residual radioactive contamination in soil. Exposure pathways included in the resident farmer scenario include external exposure to penetrating radiation, inhalation exposure to resuspended soil, ingestion of soil, and ingestion of contaminated drinking water, plant products, animal products, and fish. The predefined conceptual models within DandD are geared at assessing releases of radioactivity, transport to and exposure along these pathways.

For the building occupancy scenario, DandD models external exposure to penetrating radiation as an infinite area source using surface source dose rate factors from Federal Guidance Report No. 12 (EPA, 1993). Exposure to inhalation of resuspended surface contamination is modeled as a linear static relationship between surface contamination and airborne concentrations. The model accounts for ingrowth and decay. Exposure to incidental ingestion of surface contamination is modeled with a constant transfer rate.

The generic conceptual models for the resident farmer scenario are more complicated because of the large number of exposure pathways and considerations of release of radioactivity from the source area and transport of radionuclides in the environment. DandD models external exposure from volume soil sources when the person is outside as an infinite slab of contamination six inches thick using dose rate factors from Federal Guidance Report No. 12 for volume contamination. When the person is indoors, exposure from external radiation is modeled in a similar manner except the exposure is assumed to be attenuated through the use of a shielding factor (note: the higher the shielding factor, the lower the assumed attenuation). Exposure through ingestion of contaminated animal and plant products is modeled simply through the use of transfer factors.

Instantaneous equilibrium is assumed to occur between radionuclide concentration in the soil and the concentration in plants and between animal feed and animal products.

The generic source term conceptual model in DandD assumes a constant release rate of radionuclides into the water and air pathways. Release of radionuclides by water is assumed to be downward and a function of a constant infiltration rate, constant contaminant zone thickness, constant moisture content, and equilibrium adsorption. DandD assumes that there are no radioactive gas or vapor releases. Release of radioactive particulates is assumed to be upward, instantaneous, uniform, and a function of a constant particulate concentration in the air and the radioactivity within the soil. Radionuclides in the contaminant zone are assumed to be uniformly distributed in a single soil layer, 0.15 meters thick. No transport is assumed to occur within the source zone, but radioactive decay is taken into account. In terms of containment, DandD assumes that there are no containers (or that they have failed) and that there is no cover over the contaminated zone.

The DandD generic conceptual model for the ground-water pathway assumes a single hydrostratigraphic layer for each of the unsaturated and saturated zones. The unsaturated zone (vadose zone) can be broken into multiple layers within DandD; however, each layer is assumed to have the same properties. For radionuclides entering the vadose zone, DandD accounts for adsorption-limited leaching by considering the vadose zone to behave as a well-mixed chemical reactor with a constant water inlet and outlet rate set at the infiltration rate. Accordingly, it is assumed that the vertical saturated hydraulic conductivity of the unsaturated zone is greater than or equal to the infiltration rate (i.e., there is no ponding or runoff on the surface). The outlet concentration from one unsaturated zone layer to another is assumed to be a function of the constant infiltration rate, equilibrium partitioning, the thickness of the layer, a constant moisture content, and radioactive decay. Radionuclides entering the saturated zone are assumed to be instantaneously and uniformly distributed over a constant volume of water equivalent to the larger of either the volume of infiltrating water (i.e., the infiltration rate times the contaminated area) or the sum of the water assumed to be removed for domestic use and irrigation. Based on the default parameters in DandD Version 1.0, dilution in the ground-water pathway is based on the water use. The volume of water that radionuclides is assumed to be diluted in is roughly equivalent to 1250 m^3 (44,100 ft^3). No retardation is assumed to occur in the aquifer; however, radioactive decay is taken into account. A volume of contaminated water equivalent to the irrigation volume is assumed to be returned annually to the source zone. The concentration of radionuclides in the irrigation water is assumed to remain constant during the year. Radionuclides deposited on the vegetation are assumed to be removed at a constant rate. The DandD ground-water model should generally provide a conservative representation of the ground-water system because it allows very little dilution and nominal attenuation.

The generic surface-water conceptual model in DandD assumes that radionuclides are uniformly mixed within a finite volume of water representing a pond. The default pond volume in DandD Version 1.0 is 1300 m^3 (46,000 ft^3). Radionuclides are assumed to enter the pond at the same time and concentration as they enter the ground water. Accordingly, there is assumed to be no transport of radionuclides through the ground water to the pond and thus no additional attenuation (besides the initial ground-water dilution) is assumed for transport in the ground water. The surface-water model within DandD should provide a conservative dose estimate as long a small

volume is assumed for the surface water pond. Because the parameters in DandD are selected to provide a conservative dose estimate, the generic conceptualization of the surface-water pathway should generally provide a conservative representation of transport of radionuclides through the

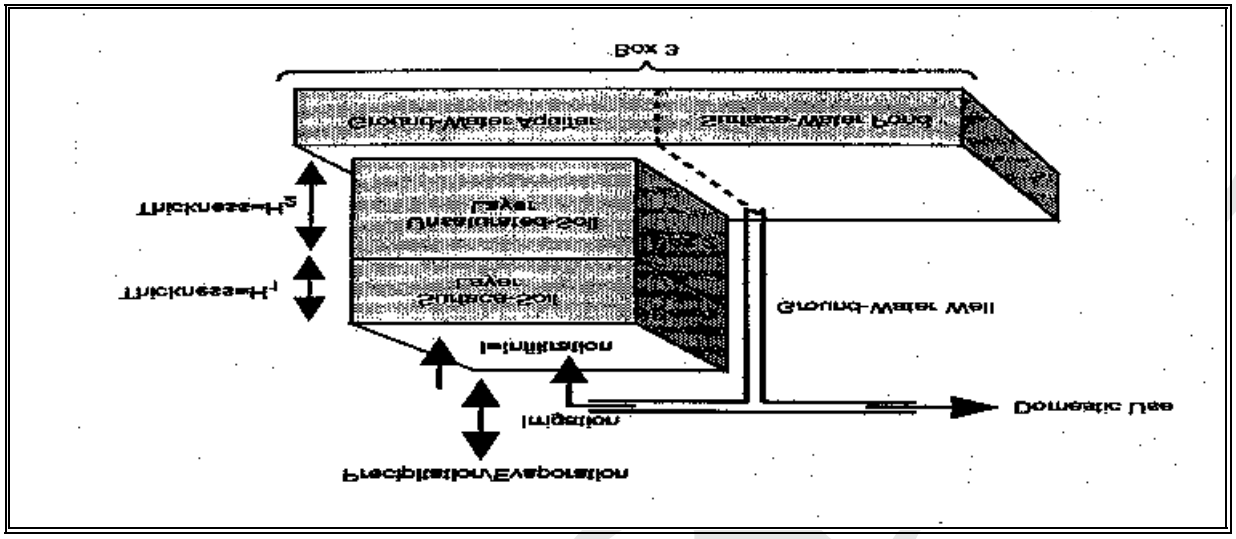

Figure C5.3 DandD conceptual model of the ground-water and surface-water systems (from Cole et al., 1998).

surface-water pathway. Figure C5.3 shows the generic ground-water and surface-water conceptual model within DandD.

The generic conceptual model of the air pathway in DandD assumes an equilibrium distribution between radionuclides in the air and soil. The concentration in air is assumed to be a function of the soil concentration and a constant dust loading in the air. Accordingly, all radionuclides in the air are assumed to be in a particulate form. The air pathway model within DandD is very simple and should generally allow a conservative dose estimate as long as a conservative particulate concentration is assumed. For DandD Version 1.0, a default particulate concentration of 4×10^{-4} g/m^3 is assumed for the garden area and 3.14×10^{-6} g/m^3 for the rest of the outdoors. Because the default parameters in DandD are geared to be conservative, in general the air pathway in DandD should allow a conservative dose estimate.

In general, the conceptual models within DandD are expected to provide a conservative representation of site features and conditions. Therefore, for screening analyses, NRC will consider such generic conceptual models to be acceptable provided it is acceptable to assume that the initial radioactivity is contained in the top layer (building surface or soil) and the remainder of the unsaturated zone and ground water are initially free of contamination. In using DandD for site-specific analyses, it is important to ensure that a more realistic representation of the site that is consistent with what is known about the site would not lead to higher doses. Some site features and conditions that may be incompatible with the generic conceptual models within DandD are listed in Table C5.1.

For any site where it is known that one or more of these conditions or features are present, the

Table C5.1 Site features and conditions that may be incompatible with those assumed in DandD.

Sites with highly heterogeneous radioactivity, Sites with wastes other than soils (e.g., slags and equipment), Sites that have multiple source areas, Sites that have radionuclides that may generate gases (e.g., H-3 and C-14), Sites that have contaminated zones thicker than 0.15 meters, Sites with chemicals or a chemical environment that could facilitate radionuclide releases (e.g., colloids), Sites with soils that have preferential flow conditions that could lead to enhanced infiltration, Sites with a perched water table, surface ponding, or no unsaturated zone, Sites where the ground-water discharges to springs or surface seeps, Sites with existing ground-water contamination, Sites where the potential ground-water use is not expected to be located immediately below the contaminated zone, Sites with significant transient flow conditions, Sites with significant heterogeneity in subsurface properties, Sites with fractured or karst formations, Sites where the ground-water dilution would be less than 2000 m^3 (70,000 ft^3), Sites where overland transport of contaminants is of potential concern, Sites with radionuclides that may generate gases, and Sites with stacks or other features that could transport radionuclides off the site at a higher

licensee should provide an appropriate rationale on why the use of the DandD will not result in an underestimation of potential doses at the specific site.

As example, it may be possible to demonstrate the acceptable use of DandD for analyzing sites that contain ^{3}H and ^{14}C, although both radionuclides may be occur as a gas. The following approach can be used to demonstrate the acceptable use of DandD for analyzing sites that contain either ^{3}H or ^{14}C (Haaker, 1999): (1) determine the area of the contaminated zone, (2) run DandD for the site with only ^{3}H or ^{14}C, (3) read the associated activity ratio factor for the given area from Figure C5.4, and (4) estimate the potential missed dose by multiplying the inhalation dose calculated from DandD by the activity ratio factor.

5.3.2 Site-specific

For site-specific analyses, the intent is to provide a more realistic assessment of doses based on more site-specific information and/or data. Presumably for such analyses, more is known about the

site from which to develop a conceptual model. For site-specific analyses the licensee should provide a schematic or verbal description of the problem that they are attempting to analyze. Even when using a computer code that has a predefined conceptual model, it is important for the licensee to identify any site features or conditions that may differ from those assumed in the code. In developing a site-specific conceptual model or identifying potential limitations with a predefined conceptual model, the issues listed in Table C5.2 should be considered.

Table C5.2 Issues to be considered in developing a site-specific conceptual model.

Whether a more realistic representation of the site would lead to higher doses; Whether the conceptual model accounts for the most important physical, chemical, and biological processes at the site; Whether the conceptual model adequately represents responses to changes in stresses; and Whether the conceptual model includes consistent and defensible assumptions.

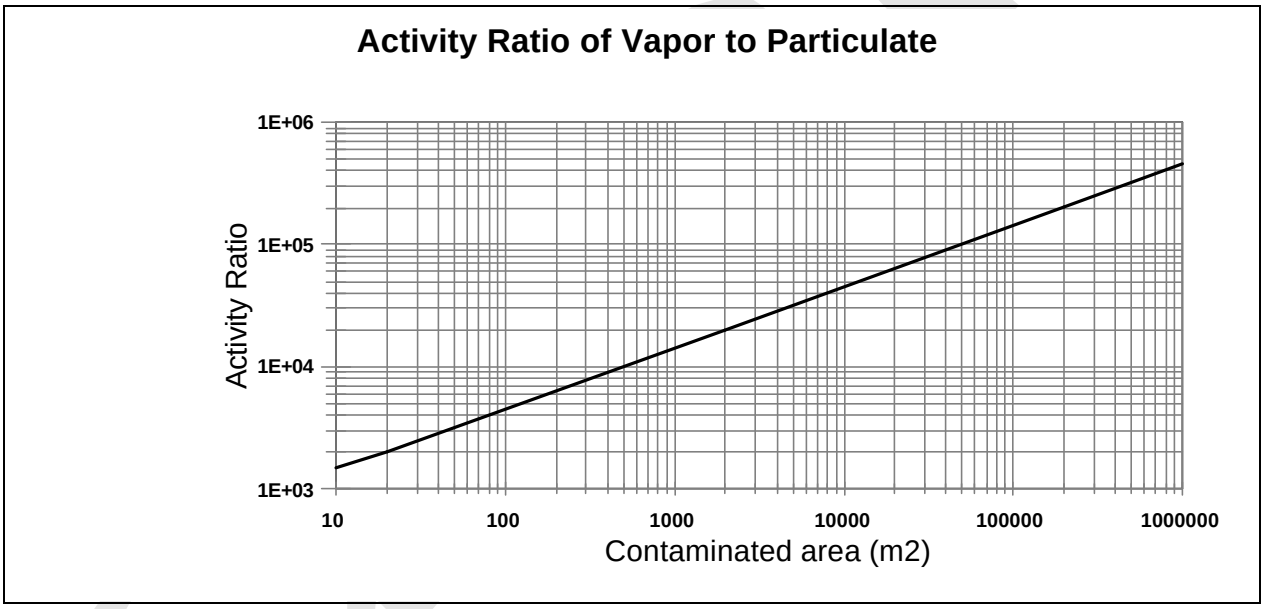

Figure C5.4 Activity ratio of vapor to particulate as a function of contaminated area.

Because conceptual models are developed based on limited data, in most cases more than one possible interpretation of the site can be justified based on the existing data. This uncertainty should be addressed by developing multiple alternative conceptual models and proceeding forward with the conceptual model(s) that provide the most conservative estimate of the dose and yet is consistent with the available data. Consideration of unrealistic and highly speculative conceptual models should be avoided. Consistent with the overall dose modeling framework of starting with

simple analyses and progressing to more complex modeling as warranted, it may be advisable for the analyst to begin with a simple, conservative analysis that incorporates the key site features and processes and progressing to more complexity only as merited by site data. It is important to stress that a simple representation of the site in of itself does not mean that the analysis is conservative. It is incumbent upon the licensee to demonstrate that their simplification is justified based upon what is known about the site and the likelihood that alternative representations of the site would not lead to higher calculated doses.

In general, there are two primary areas of the dose analysis where the conceptual model is expected to change from one site to another; these are related to the source term and environmental transport. Aspects of the analysis related to the exposure pathways in the biosphere and dosimetry are largely determined by the scenario and the assumed behavior of the critical group. Accordingly, models related to the exposure pathways in the biosphere and dosimetry should not change from one site to another unless there is a significant change in the scenario and associated critical group. The principal environmental transport pathways that will have to be considered in a dose assessment are ground water (including transport through the unsaturated zone), surface water, and air.

The conceptual model of the source area should describe the contaminants and how they are likely to be released into the environment. Specifically, it should describe key features and processes such as the infiltration of water into the source area, the geometry of the source zone, the distribution of contaminants, release mechanisms, the physical form of the contaminants, near-field transport processes, and containment failure. If the contaminants are assumed to be uniformly distributed, this is an important assumption that needs to be justified because in general contaminants will not be uniformly distributed (see discussion under Criteria for Source Term Abstraction). The source description should clearly identify how the contaminants are assumed to be released from the media. Common release mechanisms are diffusion, dissolution, surface release, and gas generation. The source description should also identify key processes and features that may retain or limit the release of contaminants from the source area (e.g., solubility and sorption). In addition, the description of near-field transport should state assumptions made regarding the dimensionality. In general, the assumption of one-dimensional vertical flow should be appropriate unless there is some type of barrier present which may hinder flow in the vertical direction. The description of the source term should also describe failure mechanisms for any containment (e.g., corrosion, concrete degradation, or cover degradation) if containers or other forms of containment are present.

The conceptual model of the ground-water pathway should describe how contaminants could migrate through the unsaturated and saturated zones to potential receptors (e.g., a well, spring, or surface-water bodies). Essential features that should be included in the conceptual model include hydrostratigraphic units, information on the geometry of the pathway (i.e., boundaries and boundary conditions), the physical form of the contaminants (i.e., dissolved, suspended sediment, gas, etc.), structural features of the geology (i.e., those that influence contaminant transport such as fractures, faults, and intrusions), and physical and chemical properties. Important processes that should be characterized include the dimensions and state conditions (e.g., steady-state) of flow, dimensions and state conditions of transport (e.g., dispersion), chemical and mass transfer processes (e.g., sorption, precipitation, complexation), and transformation processes (e.g.,

radioactive ingrowth and decay). While contaminant migration through both the unsaturated and saturated zones is best represented in three-dimensions, it may be appropriate to assume only one- or two-dimensions, if this provides a more conservative representation of contaminant migration and/or if it can be demonstrated that migration in one or more other directions is not expected to result in exposure to potential receptors.

The conceptual model of the surface-water pathway should describe potential contaminant migration through surface-water bodies such as lakes, streams, channels, or ponds to potential receptors. Essential features that should be included in the conceptual model include the geometry of the surface-water body (i.e., boundaries and boundary conditions), the physical form of the contaminants (e.g., dissolved or solid), and physical and chemical properties. Key processes that should be described include the dimensions and state conditions of flow and transport, chemical and mass transfer processes (e.g., sorption, precipitation, volatization), and transformation. One key boundary condition that should be described is how the contaminants are expected to initially mix or interact with the surface water.

The conceptual model of the air pathway should describe potential contaminant migration through the air to potential receptors. Essential features that should be included in the conceptual model are similar to those for the other environmental pathways, namely, the geometry (i.e., boundaries and boundary conditions), form of contaminants (e.g., particulates or gases), and physical and chemical properties. Key processes that should be described include the dimensions and state conditions of flow and transport, and transformation processes.

5.3.2.1 Site-specific Computer Codes

Two common computer codes used for site-specific analyses are RESRAD and RESRAD-BUILD. Both of these computer codes have predefined conceptual models. Therefore, in using these codes, it is important for the licensee to demonstrate that key site features and conditions are consistent with the modeling assumptions within the codes or where they are not consistent, the analysis will not result in an underestimation of potential doses.

5.3.2.1.1 RESRAD-BUILD

The RESRAD-BUILD code can be used to evaluate doses for the building occupancy scenario. It considers exposure from external radiation at the source and air submersion, inhalation of airborne material, and inadvertent ingestion of radioactive material. Exposure to direct radiation at the source is calculated using surface source dose rate factors from Federal Guidance Report No. 12. RESRAD-BUILD incorporates correction factors to account for a finite area source, for any offset of the receptor from the axis of the disk of contamination, and for shielding by material covering the contamination. Exposure to external radiation from air submersion is calculated as an infinite cloud of material using dose rate conversion factors for an infinite cloud. RESRAD-BUILD models airborne concentration of radionuclides using a dynamic model that accounts for the kinetic introduction and removal of radioactive material to and from indoor air. Exposure to incidental ingestion of radioactive material is modeled using a constant transfer rate.

5.3.2.1.2 RESRAD

RESRAD can be used for analyzing the resident farmer scenario. As with the generic conceptual models used by DandD for analyzing the resident farmer scenario, the conceptual models in RESRAD (see Figure C5.5) are more complex than those in RESRAD-BUILD. RESRAD models external exposure from volume soil sources when the person is outside using volume dose rate factors from Federal Guidance Report No. 12. Correction factors are used to account for soil density, areal extent of contamination, thickness of contamination, and cover attenuation. When the person is indoors, exposure from external radiation is modeled in a similar manner except that additional attenuation is included to account for the building. Exposure through ingestion of contaminated animal and plant products is modeled simply through the use of transfer factors.

The generic source term conceptual model in RESRAD assumes a time-varying release rate of radionuclides into the water and air pathways. Radionuclides in the contaminant zone are assumed to be uniformly distributed. No transport is assumed to occur within the source zone, but radioactive decay is accounted for. In terms of containment, the radioactive material is not assumed to be contained (or containers are assumed to have failed). RESRAD does allow inclusion of a cover over the contaminated area. However, the cover is not assumed to limit infiltration of water, and is assumed to function only in terms of providing shielding from gamma radiation. Release of radionuclides by water is assumed to be a function of a constant infiltration rate, time-varying contaminant zone thickness, constant moisture content, and equilibrium adsorption. The contaminant zone is assumed to decrease over time due to a constant erosion rate. RESRAD assumes a uniform release of tritium and C-14 gases based on a constant evasion loss rate. Particulates are assumed to be instantaneously and uniformly released into the air as a function of the concentration of particulates in the air based on a constant mass loading rate.

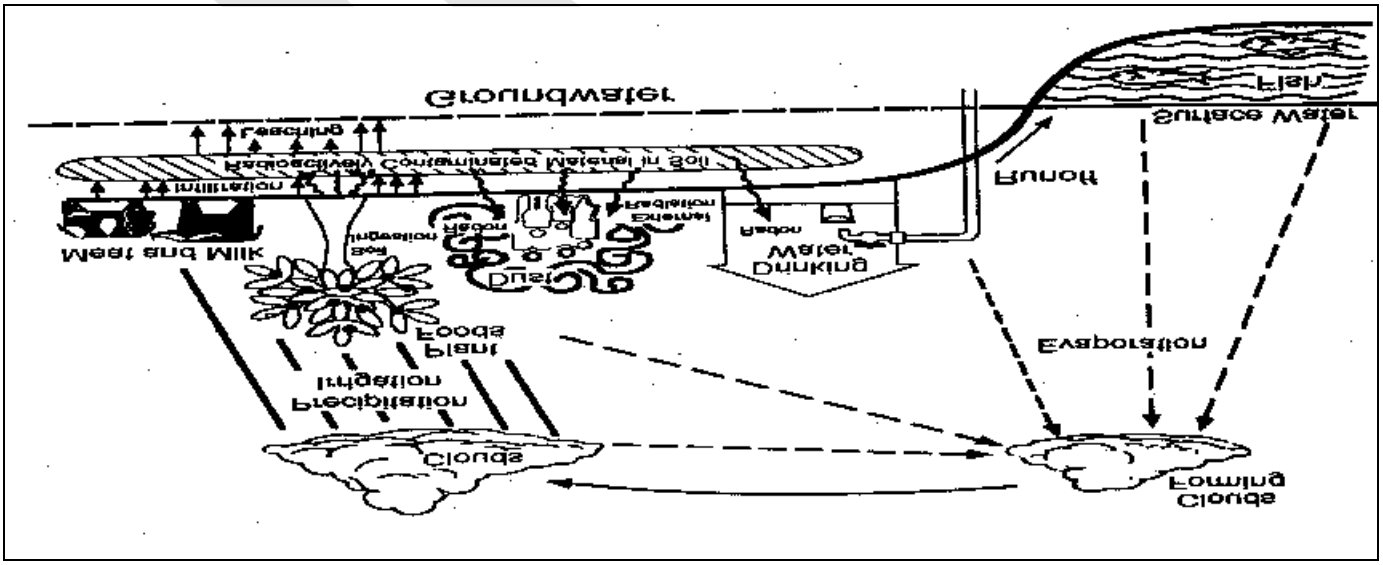

Figure C5.5 Conceptualization modeled by RESRAD (from Yu et al., 1993).

The RESRAD generic conceptual ground-water model assumes one or more horizontal homogeneous strata for the unsaturated zone. Transport in the unsaturated zone is assumed to result from steady-state, constant vertical flow, with equilibrium adsorption, and decay, but no dispersion. RESRAD has two different ways of modeling radionuclides once they reach the saturated zone. In one approach, radionuclides entering the saturated zone are assumed to be instantaneously and uniformly distributed over a constant volume equivalent to the volume of water removed by the hypothetical well (as long as the pumping rate is larger than the rate of leachate entering the ground-water. If not, no dilution is assumed to occur in the ground-water); this is known as the mass-balance approach. For the mass balance approach, radionuclides are assumed to enter a well pumping immediately beneath the contamination zone. The mass balance approach is very similar to the ground-water modeling approach in DandD. In the other approach, transport in the saturated zone is assumed to occur in a single homogeneous stratum, under steady-state, unidirectional flow, with a constant velocity, equilibrium adsorption, and decay. This second approach is referred to as the nondispersion approach. It assumes no dispersion; however, radionuclides are assumed to be diluted by clean water as a function of the assumed capture zone of the hypothetical well in relation to the width of contamination and the depth of contamination in relation to the depth of the hypothetical well. Radioactive decay and equilibrium adsorption are assumed to occur for the nondispersion approach. Further, radionuclides are assumed to enter a well located at the immediate down-gradient edge of the contamination zone. For the nondispersion model, the calculated width of the effective pumping zone could be a factor of two larger than what one would predict from a steady-state capture zone analysis; this could lead to a slight overestimation in the amount of dilution (Haaker et al., 1999).

In determining which of these two conceptual models to use, consideration must be given to where the hypothetical well will be located (i.e., either at the center of the contamination or at the edge of the contamination), the relative half-life of the radioactivity, and the potential capture zone of the hypothetical well. Use of the nondispersion model will generally result in lower estimated doses. Both models assume that radionuclides enter the well as soon as they reach the water table. However, the nondispersion model, unlike the mass balance model, calculates the time it takes for the peak concentration to occur following the initial breakthrough. Accordingly, the nondispersion model accounts for radioactive decay during the interval between the initial breakthrough and arrival of the peak concentration. Generally, the amount of decay should be small unless the radionuclides have short half-lives and are retarded. In addition, unlike with the mass balance model, for the nondispersion model no assumption is made that all radionuclides released from the contaminated zone are withdrawn through the well. Therefore, the nondispersion model will generally include dilution. The only way that dilution is not considered is if the expected capture zone of the hypothetical well is small in relation to the width and thickness of the contamination. Because the nondispersion model will generally give a lower estimated dose than the mass balance model, it is important for the analyst to justify the use of this model for the specific analysis. Use of the mass balance approach should always be acceptable. Use of the nondispersion model should be acceptable, without additional justification, for modeling long-lived radionuclides (i.e., where radioactive decay is not important) when either of the following conditions are met:

$$\frac{U_w}{\bar{v} \bullet d_w} > \frac{A}{len} \quad \text{and}$$

$$\left(\frac{I}{\bar{v}}\right) len < d_w \quad \text{or}$$

$$\frac{U_w}{\bar{v} \bullet d_w} \leq \frac{A}{len} \quad \text{and}$$

$$\left(\frac{I}{\bar{v}}\right) len \geq d_w$$

Where:

U_w / pumpage rate from the well (m^3/y)
v / ground-water darcy velocity (m/y)
A / area of contamination (m^2)
d_w / depth of well intake below water table (m)
len / length of contamination parallel to ground-water flow (m)
I / infiltration rate (m/y)

As a general rule, use of the nondispersion approach should be acceptable when the area of contamination is known to be larger than the assumed capture area of the hypothetical well. Assuming an essentially flat water table and steady-state conditions, the capture area of the hypothetical well can be calculated as follows:

$$A_w = \left(\frac{U_w}{I}\right)$$

Where:

$A_w \equiv$ area of well capture (m^2)

$U_w \equiv$ pumpage rate from the well (m^3 / y)

$I \equiv$ infiltration rate (m / y)

The generic conceptual model of the surface-water pathway in RESRAD assumes that radionuclides are uniformly distributed in a finite volume of water within a watershed. The default watershed area in RESRAD Version 5.91 is $1x10^6$ m^2 (250 acres). Radionuclides are assumed to enter the watershed at the same time and concentration as in the ground water. Accordingly, no additional attenuation is considered as radionuclides are transported to the watershed. In the surface water, radionuclides are assumed to be diluted as a function of the size of the contaminated area in relation to the size of the watershed. The RESRAD surface-water conceptual model assumes that all radionuclides reaching the surface-water are derived from the ground-water pathway. Thus, transport of radionuclides overland from runoff is not considered. In addition, additional dilution from overland runoff is not considered.

The generic conceptual model of the air pathway in RESRAD uses a constant mass loading factor and area factor to model radionuclide transport. The area factor, which is used to estimate the amount of dilution, relates the concentration of radionuclides from a finite area source to the concentration of radionuclides from an infinite area source. It is calculated as a function of particle diameter, wind speed, and the side length of a square area source. The conceptual model assumes a fixed particle density, constant annual rainfall rate, and constant atmospheric stability. No radioactive decay is considered. See Chang et al. (1998) for more detail. Tritium and C-14 gases are assumed to be uniformly mixed in a constant volume of air above the contaminated zone. RESRAD does not model the transport of tritium and C-14 as particulates in the air.

5.3.2.2 Limitations of Site-specific Computer Codes

In general, the conceptual models within RESRAD and RESRAD-BUILD are expected to provide an acceptable generic representation of site features and conditions. Some specific site features and conditions that may be incompatible with this generic representation are listed in Table C5.3.

Any site where it is known that one or more of these conditions or features are present, the licensee should provide appropriate justification for use of the computer code.

5.4 Generic Examples

5.4.1 Screening

A hypothetical research and development (R&D) facility is authorized to use radiological chemicals through an NRC license. Because the R&D facility plans to discontinue their use of radiological chemicals, they want to decommission the facility and terminate their license. A historical site assessment reveals that use of radiological chemicals were limited to a single building within the facility. The floor area of the facility is estimated to be 6,000 ft^2 (560 m^2). The wall area is 4,600 ft^2 (430 m^2). In addition, an outside area of roughly 10,000 ft^2 (4600 m^2) was used for dry storage of chemicals. A preliminary characterization program has determined that approximately 10% of the building floor area and 5% of the wall area are contaminated with ^{137}Cs and ^{60}Co. Surficial soils covering an area of approximately 27,000 ft^2 (2500 m^2) are contaminated from windblown dust and runoff from spills in the storage area. The soils are also contaminated with ^{137}Cs and ^{60}Co.

Table C5.3 Site feature and conditions that may be incompatible with the assumptions in RESRAD.

Sites with highly heterogeneous radioactivity, Sites with wastes other than soils (e.g., slags and equipment), Sites with multiple source areas, Sites that have chemicals or a chemical environment that could facilitate radionuclide releases, Sites with soils that have preferential flow conditions that could lead to enhanced infiltration, Sites where the ground-water discharges to springs or surface seeps, Sites where the potential ground-water use is not expected to be located in the immediate vicinity of the contaminated zone, Sites with significant transient flow conditions, Sites with significant heterogeneity in subsurface properties, Sites with fractured or karst formations, Sites where overland transport of contaminants is of potential concern, and Sites with stacks or other features that could transport radionuclides off site at a higher concentration than on site.

The licensee proposes to use a screening analysis, using DandD, to demonstrate compliance with the license termination rule. A building occupancy scenario is assumed for the building and a residential farmer scenario is assumed for the contaminated soils. Based upon what is known about the site, the licensee certifies that the use of the generic conceptual models within DandD is appropriate for the analysis.

5.4.2 Site-specific

A hypothetical manufacturing facility has a former radioactive waste burial area that will be decommissioned for unrestricted release. Radioactively contaminated trash was previously buried in 55-gallon drums, in trenches covering an area of roughly 2000 m^2. The trenches, which are roughly 0.9 meters deep are covered with 1.2 meters of native soil. A review of site operating records show that the radionuclides of concern are natural uranium, enriched uranium, and natural thorium.

Based on information from the local county agricultural extension office and published reports, the geology and hydrogeology at the site are described as follows:

> The surface geology at the site contains 14 to 27 meters of till consisting primarily of fine, silty sand to sandy silt with narrow, discontinuous sand lenses. Sandstone bedrock underlies the unconsolidated till. A shallow unconfined aquifer occurs in the unconsolidated till. The average depth to the water table ranges between three to four meters below the land surface. The mean horizontal hydraulic conductivity is roughly 60

m/y. The average vertical hydraulic conductivity of the till is estimated to be an order of magnitude less. The hydraulic gradient is estimated to range between 0.006 to 0.021. The mean precipitation at the site is roughly 0.8 m/y. The site is located in the reach of a surface water drainage basin that has a drainage area of approximately 500,000 m^2.

A residential farmer scenario is assumed as a reasonable future land use. The licensee proposes to use the RESRAD computer code for the dose analysis. Because the contaminated media is trash, an assumption is made that the trash degrades and becomes indistinguishable from soil. In addition, the metal drums are assumed to have degraded away. Given the relative short lifespan for metal drums and the long half-life of the radionuclides, this should be a reasonable assumption. The cover is also assumed to be breached through the construction of a basement for the house. The contaminated soil is assumed to be uniformly mixed with the excavated cover. Because the trash is assumed to be indistinguishable from soil, it is also assumed that once the cover is breached the future hypothetical farmer will not recognize the contaminated material as contaminated. The licensee also assumes that the hypothetical future well is located at the center of the contamination because of limited basis for assuming otherwise.

The licensee determines that the other aspects of conceptual models within RESRAD are acceptable for the analyzing the problem.

6.0 Criteria for Selecting Computer Codes/Models

6.1 Introduction

Dose assessment commonly involves execution of numerical model(s) that mathematically represent the conceptual model of the contaminated site (see Section 5.1). The numerical models, used to implement the mathematical equations are usually linked via the conceptual model and codified in a software package known as "the code." The words "code" and "model" are synonyms used frequently to express the software package including the embedded numerical models or the specific models contained in the code. For example, "DandD code" may refer to the software package including the associated exposure models (e.g., the water use model, food ingestion pathway model, inhalation exposure model etc.) embedded in the code. The "DandD model" may also refer to DandD software, the DandD conceptual model, or to any of the numerical models, or the group of models, used in the code (e.g., DandD groundwater model). Within the context of this SRP; the word "code" shall refer to the software package and the associated numerical models. However, the word "model" shall refer to the mathematical representation of the conceptual model including representation of the specific exposure scenario and pathways. This section describes the process and criteria used in selection of codes and models for the dose assessment.

The codes and models used in the dose assessment can be either generic screening codes/models or site-specific codes/models. Regardless of the intent of the code/model use (e.g., for screening or site-specific analysis), reviewers should ensure that dose assessment codes/models and the associated databases be properly documented and verified in accordance with a rigorous quality assurance (QA)/quality control (QC) criteria acceptable by the NRC. Currently, the only acceptable generic screening code is DandD version 2.0. As was indicated in Section 2.0, other generic codes/models may also be accepted on a case-by-case evaluation. In this respect, review staff should assess the QA/QC documentation and the level of conservatism of the alternate generic code/model used. In addition, staff should review the comparability with the DandD code assumptions and scenarios as well as compatibility with the site conceptual model. If site-specific models/codes are used, a justification of the conceptual model should be provided (see section 5.3.2). Staff would also review the source-term model(s), the transport models, the exposure models, and the overall dose models used.
This section describes the generic issues associated with selection of the screening and site-specific codes/models that reviewers may encounter and recommended approaches and criteria for review staff acceptance of the codes/models. In addition, this section presents generic description of the two common dose assessment codes, DandD Screen and RESRAD/RESRAD-BUILD. These codes have been, or being, developed or modified by the NRC. In addition, these codes were used by staff and licensees for demonstration of compliance with the dose criteria in 10 CFR Part 20, Subpart E. To help review staff understand the dose modeling review process, two examples are provided demonstrating use of DandD Version 2.0 and probabilistic RESRAD/RESRAD-BUILD codes.

6.2 Issues in selection of computer codes/models

The major issues pertaining to selection of computer codes/models include:

1) Generic criteria for selection of computer codes/models: this issue pertains to staff review criteria of code aspects related to QA/QC requirements, specifications, testing, verification, documentation, interfacing, and other features related to uncertainty treatment approaches.

2) Acceptance criteria for selection of site-specific codes/models: this issue involves staff review of additional specific requirements regarding justification for use of the conceptual model, the numerical mathematical models, the source-term model and its abstraction, and the transport and exposure pathway models used.

3) Options for selection of deterministic or probabilistic site-specific codes: this issue addresses staff review of justification needed to support the decision made using either of these two approaches.

Certain reviewers may be unfamiliar with NRC's newly developed models and codes. Therefore, a generic description of the DandD version 2.0 is presented to familiarize staff with this code. Further, the rationale for development of DandD version 2 and the issue of excessive conservatism in DandD version 1are also addressed. An outline is presented describing inherent excessive conservatism in DandD model and approaches to minimize excessive conservatism using DandD version 2, site-specific input data, or use of other models/codes.

The NRC also sponsored development of probabilistic RESRAD (version 6.0) and RESRAD-BUILD (version 3.0) codes for site-specific analysis. A brief description of these two codes and generic steps used in code execution are presented to familiarize reviewers with these two newly developed codes. The information presented should also help staff review of input/output data and how the codes could be executed to demonstrate compliance with the dose criteria in 10 CFR Part 20, Subpart E.

For site-specific analysis, reviewers should accept any model or code that meet the criteria described in sections 6.3.1 and 6.3.2. However, staff is expected to conduct more detailed and thorough review of less common codes/models (e.g., codes other than DandD, and RESRAD) specifically those developed by the users. Staff review of other codes (e.g., other than common codes like DandD and RESRAD) is briefly discussed in Section 6.3.3.

Selection of appropriate models/codes for complex sites may also represent a challenging task for staff review of certain complex sites. For example, sites with multiple source-terms, with significant groundwater/surface-water contamination, or sites with existing off-site releases may require more advanced codes/models than common codes such as DandD or RESRAD. Complex sites may also cover sites with engineering barrier(s), or with complex geological conditions like highly fractured geologic formations. Because of site complexity and variability, there will be no standard dose analysis review criteria for these sites. Section 6.3.4 presents generic examples for review staff to categorize a site as "complex sites" for further site-specific analysis to evaluate site performance on a case-by-case basis.

6.3 Recommended Approach

6.3.1 Generic Criteria for Selection of Codes/Models

The generic criteria under this subsection pertains to staff review of codes/models other than commonly used codes specifically those developed or modified by the NRC (e.g., other than DandD and RESRAD/RESRAD-BUILD). Specifically, staff should use the generic criteria when the selected codes/models have no readily available documentation of testing, verification, and quality assurance (QA) and Quality Control (QC) review and scrutiny. In this context, staff should use the following generic criteria in reviewing the codes/models selected for dose assessment:

- Staff should review the adequacy and completeness of the data base available regarding quality assurance (QA) and Quality Control (QC) aspects of the code/model. The QA/QC data base should be comparable to NRC's QA/QC requirements (NUREG/BR-0167 (Douglas, 1993) and NUREG-0856 (NRC, 1983)). The QA/QC should include information regarding mathematical formulation, code/model assumptions, consistency of the pathways with the assumed conceptual model(s) used in the code, and accuracy of the software to reflect model mathematical formulation and correct representation of the process or system for which it is intended.

- Staff should ensure that the software used for the code are in conformance with the recommendations of IEEE Std.830-1984, IEE Guide For Software Requirement Specifications.

- Staff should review adequacy and appropriateness of the code/model documentation with regard to: (a) software requirements and intended use, (b) software design and development, (c) software design verification, (d) software installation and testing, (e) configuration control, (f) software problems and resolution, and (g) software validation.

- For uncommon codes/models, staff should review users submitted code data including: (a) a software summary form, (b) software problem/change form, (c) a software release notice form, and (d) code/model user's manual which covers code technical description, software source code, functional requirements, as well as external interface requirements (e.g., user interface, hardware interface, software interface, and communication interface), if necessary.

- Staff should review the conceptual model of the selected code to ensure compatibility with the specific site conceptual model including the pathways and the exposure scenario. The source-term assumptions of the selected code should also be compatible with site-specific source-term. Staff may accommodate minor modifications in the source term conceptual model as long as the basic model assumptions are not violated.

- Staff should review the selected code to ascertain that the exposure scenario of the selected code is compatible with the intended scenario to be used for the concerned site. For example, models/codes designed for the onsite exposure scenario may not be appropriate for assessment of off-site receptor scenario or a scenario to estimate an off-site collective public dose.

- Staff should review the selected model/code formulation to account for radio-nuclides decay and progenies. The code should have proper and timely formulation as well as linkages of decay products with the receptor location and the transport pathways via corresponding environmental media.

- Reviewers should examine documentation of the selected code/model performance specifically test and evaluation as well as code comparison with commonly used (accepted) codes and models (e.g., such as DandD and RESRAD codes). Staff should also review documentation on code/model verification, if available, to support decisions for code acceptance.

- Staff should review code/model features regarding sensitivity/uncertainty analysis to account for variability in selection of input parameters and uncertainty in the conceptual model and multiple options for interpretation of the system.

6.3.2 Acceptance Criteria for Selection of Site-specific Codes/Models:

This issue involves staff review of additional specific requirements regarding justification for the use of the conceptual model, the numerical mathematical models, the source-term model and its abstraction, and the transport and exposure pathway models used.

- Conceptual Models: staff review shall compare the conceptual model for the specific site with the conceptual model(s) in the selected code to ensure compatibility with site-specific physical conditions and pathway assumptions for the critical group receptor (see section 5.3.2).

- The Numerical Mathematical Models: staff should review the equations used in the code to implement the conceptual model and the numerical links between mathematical models to ensure correctness and consistency. For codes developed or modified by the NRC (e.g., DandD, RESRAD & RESRAD-BUILD), staff review would be minimal because these codes were revised by staff and examined early for consistency with NRC's QA/QC requirements. For less commonly used codes, or codes developed locally by user(s), staff should verify the numerical mathematical models including the numerical links between these models. In this context, staff may examine, if necessary, each mathematical model used for the specific transport exposure pathway to ensure that the code is designed for its intended use.

  a) Source-term Models:

Staff should review the source-term model(s) used for the specific site. In this context, staff review should include the following source-term aspects:

Building occupancy scenario source-term: staff should review the historic site assessment and other relevant data regarding extent of the source-term and its depth (e.g., within 1 to 10 mm deep into the building surface or more). Based on this review staff should identify the source-term as surficial or volumetric source. In addition, staff should examine assumptions made for the loose/fixed fractions of the source. Contamination sources on surfaces that are not integral parts of the building (e.g., equipment, pipes, sewer lines) should be addressed separately because the model and exposure scenario could be different. Therefore, source-term model assumption for such surfaces should be reviewed on a case-by-case bases. Staff should also review the source-term regarding radionuclide mixture and if a constant ratio is assumed in the dose analysis. Staff should also review if surrogate radionuclides are used in the source-term model assumption. The latter two situations may require additional staff verification of the source term model and review of consistency with the intended final survey methodology. Another area of review that staff should look into is the use of multiple sources (e.g., multiple rooms) . Certain codes may use advanced source-term assumptions such as 2-3 rooms with multiple story buildings. The source term under these conditions allow for source depletion due open air circulation and common ventilation. For example, RESRAD-BUILD code model uses 2- or 3-room models with 2-or 3-story building allowing for air exchange within the rooms and source-term depletion. The indoor air quality model (e.g., building ventilation and infiltration, the indoor air concentration model as well as the adaptation of the air quality model in RESRAD-BUILD code should be reviewed to ensure consistency with the site-specific condition. Input parameters associated to these models need to be verified. Staff may accept such site-specific source-term models after assessment of compatibility of the source-term model with the conceptual model of the site. Staff should also review the physical and parameters defining the source-term to ensure consistency with site-specific conditions and the occupancy parameters to ensure consistency with the exposure scenario.

Resident Farmer Scenario Source-Term: staff shall examine the source term information to identify the source as surficial or volumetric te ensure consistency with the model in the selected code. Staff shall also review the vertical and horizontal extent of contamination to verify the model assumed for the contaminated zone and to examine if there is subsurface and/or groundwater contamination at the concerned site. For surficial source-terms, DandD model and other codes like RESRAD (assuming appropriate thickness) may be used. For volumetric sources DandD cannot be used directly before simulation of the volumetric source into a surficial source.

The source-term model should also be reviewed to examine the contaminated area and its shape to examine possible correction for the area and/or for geometry of the source. Staff shall also examine and review if a cover or a barrier is assumed at the top of contaminated zone and justification for such assumption. The cover and/or barrier issue will be examined within the context of the institutional control assumptions and the physical performance of the cover or the barrier within the compliance period (e.g., 1000 years).

Staff shall also review the physical and chemical form of the source to examine the soil leaching model assumption and the two components: sorbed mass and leached mass of the source. This review should help staff assessing source mass balance model and transport model into environmental media. In addition, review of these source-term aspects would help establishing consistencies for selection of relevant parameters. Staff should also review of source-term horizontal distribution and homogeneity and variation of source concentration with depth. Staff should use either an upper bounding value for modeling the thickness or an area weighted approach to calculate an representative thickness. In certain cases staff may evaluate the need for modeling of multiple sources and the need for more advanced subsurface source-term modeling.

b) Transport Models:

The transport models simulate transport mechanisms of contaminants from the source to the receptor. Staff should review transport models for consistency and compatibility with respect to: i) the source-term, ii) the exposure scenario defined for the critical group receptor, and iii) the simplified conceptual model which describes site-specific physical conditions. The transport models may include diffusive and advective transport of contaminants via air, surface water, and groundwater. The transport models can be overly simplified using simple conservative assumptions such that minimal characterization data would be required to execute the model(s). Transport models can also be very complex requiring advanced mathematical derivation and extensive site-specific, or surrogate, data about the site.

Considering the building occupancy scenario, the transport models of the DandD code, simple and conservative transport models for ingestion, inhalation, and direct exposure pathways. The ingestion pathway depends on the effective transfer rate of the removable surface contamination from surfaces to hands and from hands to mouth. The inhalation transport model depends largely on mechanical disturbance of the contaminated surface and resuspension of contamination in the air, and subsequently breathing of contaminated air. The external dose formulation assumes exposure from a non-uniform contamination distributed on walls, ceiling and floor of the

building surfaces of a room . This model was found to be comparable to the infinite plane source for the building occupancy scenario (Kennedy and Strange, 1992).

The DandD resident farmer scenario includes transport models of contaminants to groundwater water and surface water (e.g., three-box model that relies on transfer of contaminate through leaching) and to air (e.g., through dust mass loading and indoor resuspension). Transport models of contaminants via the air include dust loading, resuspension of contaminated soil and use of mass loading factor for deposition. Transfer of contaminants from the soil/water to plants, fish, animals, and animal products are calculated using water use model along with transfer factors, translocation factors, and bio-accumulation factors. For carbon and tritium, separate models were used as described in NUREG/CR-5512, Volumes 1, 2, and 3.

RESRAD model assumes a volumetric source with an idealized cylindrical shape of the contaminated zone (CZ) and allows for a cover at the top of the CZ if necessary. See Section 5.3.2.1.2 for details of RESRAD models and assumptions.

In general, staff should conduct a generic review of the selected code with respect to transport models and appropriateness of such models to site-specific conditions (e.g., area, source, unsaturated zone, and aquifer conditions). In addition, staff should review , for compatibility and consistency the transport model assumptions and the generic formulation pertaining to the applicable pathways of the critical group exposure scenario. The extent of transport models review depends on familiarity of NRC staff with these models. Because ceratin codes/models were commonly used and were developed or modified by the NRC (e.g., DandD, RESRAD, RESRAD-BUILD, and MEPAS) staff is more familiar with such codes. Therefore, staff review would be more expedited than using less common codes/models developed by users or other parties. Staff review should also include updated new models or code versions and studies regarding code/models testing, comparison, and verifications.

RESRAD-BUILD is more advanced code than DandD because it employs multiple sources and more advanced particulate air transport models. In other words, each contaminated location may be considered a distinct source. Depending on its geometric appearance, the source can be defined either as a volume, area, or as a point source. RESRAD-BUILD depends on erosion of the source material and transport of part of its mass into the indoor air environment, resulting in airborne contamination. RESRAD-BUILD model differs from DandD because it assumes air exchange among all compartments of the building. In other words, the model assumes that the airborne particulates are being loaded into the indoor air of the compartment

and then transported to the indoor air of all compartments of the building. In addition to air exchange between compartments, the indoor air model also simulates air exchange between compartments and the outdoor air. The models describing indoor air quality, air particulate deposition, inhalation of airborne dust, and ingestion removable material and deposited dust, are described in ANL/EAD/LD-3, 1994). The exposure pathways in RESRAD-BUILD code include: i) external radiation to radiation emitted from directly from the source, from radioactive particulates deposited onto the floors, and exposure due to submersion due to radioactive particulates; ii) inhalation of airborne radioactive particulates; and iii) ingestion of contaminated material directly from the source and airborne particulates deposited onto the surface of the building.

c) Exposure Pathway Models:

The exposure pathway models pertain to formulation of the links between the radiological contamination source, transport of contaminants within environmental media, the critical group receptor location, and behaviors of the receptor that lead to its exposure to radiological contamination through direct exposure, inhalation, and ingestion of contaminated water, soil, plants, crops, fish, meat, milk, and other dairy products, In this context, staff should review the conceptual model(s) that describe the human behaviors that lead, or control, the amount of receptor exposure. Therefore, the occupational, behavioral, and metabolic parameters describing these models should be reviewed and compared with the default model scenarios and associated parameters. Staff should review exposure model(s) and associated parameters to ensure conservatism, consistency, and comparability with site-specific conditions and scenario assumptions. NUREG/CR-5512, Volumes 1, 2, and 3, and Section 7 of this document provides detailed information regarding default parameters and approaches for changing parameters in dose modeling analysis.

d) Intakes and direct exposure Dose Conversion Factors:

Staff should review the dose conversion factors for inhalation and ingestion to ensure that the factors used are those of the U.S. Environmental Protection Agency, published in Federal Guidance Report No. 11 (EPA, 1988). Similarly, staff review should ensure use of EPA's external dose factors (e.g., for an infinite surface with soil contamination to a depth of 15 cm), published in the Federal Guidance Report No. 12 (EPA, 1993). These dose factors were selected because of consistency of the dosimetry models used in deriving these factors with NRC's regulations in 10 CFR Part 20.

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6.3.3 Options for selection of deterministic or probabilistic site-specific codes

Staff should review assessment of doses that might be performed based on a deterministic analysis approach or on a probabilistic approach. Users will have each of these two options for demonstration of compliance with the dose criteria in 10 CFR Part 20, Subpart E. Section 8.3.2 provides detailed description of staff review for deterministic and probabilistic analysis.

6.3.4 Modeling of subsurface source-term contamination:

For subsurface contamination (contamination at depths >15-30 cm.), staff shall review existing historical site data (including previous processes or practices) and site characterization data to establish an adequate conceptual model of the subsurface source specifically regarding horizontal and vertical extent of contamination. Section 3.3.3 describes approaches for subsurface source-term abstraction for dose modeling analysis.

6.3.5 Generic Description and Development of DandD Versions 1.0 and 2.0 Code and Examples of DandD Code Application:

Two scenarios are implemented in DandD, the building occupancy and the residential scenario. The building occupancy scenario relates volume and surface contamination levels in existing buildings (presumably released following decommissioning for unrestricted commercial or light industrial use) to estimates of the total effective dose equivalent (TEDE) received during a year of exposure with the conditions defined in the scenario. The exposure pathways for this scenario include external exposure, inhalation exposure, and secondary ingestion.

The more complex and generalized residential scenario is meant to address sites with contamination in soils and groundwater. The exposure pathways include external exposure, inhalation, and ingestion of contaminated crops, meat, soil, plants, fish, and drinking water (Kennedy and Strenge, 1992). A generic water-use model was developed to permit evaluation of the annual TEDE from drinking water from wells and from multiple pathways associated with contaminated soil. Section 5.3.1 describes the 3-box water-use model of DandD code. .

6.3.5.1 Development Documentation of DandD Software (Version 1)

DandD assists NRC staff and licensees who must decontaminate lands and structures in determining the extent of decommissioning required to allow unrestricted release of their property. The DandD software automates the scenarios, models, mathematical formulations, and assumptions documented in NUREG/CR-5512, Volume 1 (Kennedy and Strenge, 1992). The NRC issued on August 20, 1998 the screening computer code DandD Version 1 to calculate the screening values for demonstration of compliance with the radiological criteria for the license termination rule in 10 CFR Part 20, Subpart E. The source code and the user manual for DandD Version 1 are documented in NUREG/CR-5512 Volume 2 (Wernig et al., 1999). The default parameters values in DandD Version 1 have

been defined through a systematic process of assessing the variability of each parameter across the U.S. and then defining default values that produce generic dose estimates that are unlikely to exceed at any real site (Beyeler et al., 1999). NRC staff conducted test and evaluation of the code performance and conducted code/model comparison with the deterministic RESRAD and RESRAD-BUILD codes (Haaker et al., 1999). Staff also solicited licensees and stakeholders to examine DandD Version 1 performance for real sites. Staff and users identified several areas where DandD Version 1 may be overly conservative.

6.3.5.2 Excessive Conservatism in DandD Version 1 Methodology and Parameters:

As was indicated above, the DandD, Version 1, is a deterministic screening code with a single set of default parameters which is an acceptable screening tool to calculate the screening values to demonstrate compliance with the dose limit in 10 CFR Part 20. The staff has examined several areas where the DandD code may be overly conservative. These areas include (1) reevaluation of the resuspension factor (RF), (2) reevaluation of default parameter selection, (3) model comparison study (Haaker et al., 1999), and (4) groundwater model comparison study (Cole et al., 1998). A technical basis document for revision of the RF is still under review development.

Version 1 of the DandD code uses a deterministic set of default parameters. These deterministic values however were selected from a range of possible values rather than by establishing single bounding values. A probability density function (PDF) was established for the range of values for each parameter in the DandD code. A single set of default parameters was selected by probabilistically sampling the PDFs for each of the parameters to maintain a 90 percent confidence level that doses would not exceed the dose limit for a combination of all radionuclides. A detailed discuss of the way the default parameters were selected is contained in NUREG/CR-5512, Volume 3.

This method of selecting the default parameter set tends to overestimate the dose. That is, if the default parameter set was selected for a single radionuclide rather than for all radionuclides, the dose calculated using DandD with the single radionuclide default parameter set would in most cases be lower than with the “all radionuclides” default parameter set currently in version 1 of the DandD code. For example, the DCGL corresponding to 25 mrem/yr for Cs-137 using the “all radionuclide” default parameter set is approximately 1 pCi/g; while the DCGL using the “single radionuclide” default parameter set is approximately 11 pCi/g. The results of the results of DandD, version 1 using the two default parameter sets is discussed in a letter report from Sandia National Laboratories dated January 30, 1998. To improve this area, version 2 of the code was developed to calculate a unique default parameter set based on the radionuclides in the source term.

To evaluate the overall conservatism in DandD, a study was conducted to compare the DandD code with the RESRAD and RESRAD-BUILD codes for both the residential and building occupancy scenarios respectively. This comparison is documented in NUREG/CR-5512 Volume 4 (Haaker et al., 1999). In summary, the models in the DandD codes appeared appropriate for screening (e.g., simplistic, and defensible with minimal data) The default soil mass loading factor for foliar deposition for DandD appears to be too high. The soil-to-plant transfer factors, distribution coefficients, and bio-accumulation factors for certain radionuclides appeared to be too conservative. This conservatism is mainly due to DandD Version 1 approach for selection of the solution vector to generate a single set of default parameters for all radionuclides. Therefore, the deterministic DandD code in Version 1 has been revised into a probabilistic code version 2. An arithmetic error was also found in the default parameter value of S-35 radionuclide. Also, the code does not model tritium and carbon-14 realistically. This could lead to an underestimation of doses where groundwater is not a predominate pathway. It was also determined that RESRAD and RESRAD-Build may be better suited to deal with hot spots.

Another area where we evaluated the excess conservatism in the DandD code was the groundwater model. The basic conceptual groundwater model in DandD as was described in NUREG/CR-5512, Volume 1. This groundwater model was compared with two more realistic groundwater models in NUREG/CR-5621 (Cole et al., 1998). These two models are: the STOMP code as the realistic vadose zone model and the CFEST code as the realistic aquifer compartment model. The study concluded that the maximum groundwater concentration increased with the number of vadose zone compartments for the DandD model and that it exaggerated vadose zone dispersion. The study recommended that the maximum vadose zone compartment (layer) thickness in the DandD code should be set to 1 meter. This could be a problem where the vadose zone is thicker than 10 meters, because the DandD code only allows ten vadose zone compartments. In general, PNNL concluded that the DandD model described realistic and conservative representations of an aquifer and vadose zone that are appropriate for site assessment. However, PNNL stated that for radionuclides with short half-lives compared to the vadose zone transit time, the DandD model may not be adequate.

6.3.5.3 Development of Probabilistic DandD Version 2

Due to this overly conservative approach resulting from the artifact in the way the single default parameter set was selected, staff has developed a probabilistic DandD Version 2. The screening DandD code Version 2 updates, improves, and significantly enhances the capabilities of Version 1.0. In particular, Version 2.0 allows full probabilistic treatment of dose assessments, whereas, Version 1.0 embodied constant default parameter values and only allowed deterministic analyses. DandD implements the methodology and information contained in NUREG/CR-5512, Volume 1 as well as the parameter analysis in Volume 3 that

established the probability distribution functions (PDFs) for all of the parameters associated with the scenarios, exposure pathways and models embodied in DandD.

Finally, DandD Version 2.0 includes a sensitivity analysis module that assists licensees and NRC users to identify those parameters in the screening analysis that have the greatest impact on the results of the dose assessment. Armed with this information and the guidance available in NUREG-1549, licensees are able to make informed decisions regarding allocation of resources needed to gather site-specific information related to the sensitive parameters. When cost and likelihood of success associated with acquisition of this new knowledge are considered, licensees are better able to optimize the costs to acquire site data that allow more realistic dose assessments that, in turn, may lead to demonstrated and defensible compliance with the dose criteria for license termination.

6.3.5.4 Example of DandD Code Applications

Non-Fuel-Cycle Nuclear Facilities and Generic R&D Facilities

NRC licensees use radioactive materials for an extremely broad range of activities. These might include handling byproduct, source, and/or special nuclear materials not involved in electric power production; use of radioisotopes in universities, medical institutions, and laboratories; source manufacturers; various industrial users; and R&D facilities. Many of these facilities use sealed sources or small amounts of short-lived radionuclides in their applications. Levels of exposure and contamination are often low or negligible but can be substantial in some operations.

Sealed source nuclides may include Co-60, Cs-137, I-125, Ir-192, Sr-90, and Am-241. Sealed sources are designed and tested to prevent leakage, thus contamination of structures and soils is generally not expected from routine operations. When low probability leakage events do occur, the contamination is localized and remediation is straightforward. Sealed source manufacture can involve significant operations that result in localized contamination.

Short-lived nuclides, primarily licensed for medical diagnostics, may include Tc-99m, I-131, and I-123. The nature of operation of these short-lived materials usually means contamination of structures and soils is unlikely. Any contamination is often confined to localized areas in buildings. Remediation is relatively easy and many of these materials are allowed to “decay-in-storage.” Demonstration of compliance for sealed sources and short-lived materials following cleanup may include a final survey and calculation of the reduction of activity following cleanup and decay in storage.

Case 1: Localized building contamination from Co-60 and Cs-137.
(Information will be provided after completion of DandD Version 2)

Case 2: Greater levels of contamination from Sr-90 and Am-241 leakage.

(Information will be provided after completion of DandD Version 2)

Power, Research, and Test Reactors

The major reactor facilities can involve complex patterns of contamination from a variety of normal and off-normal operations. This example is limited to use of the residential scenario to analyze the impact of releases of Co-60, Sr-90, and Cs-137 in various configurations.

Case 1: General contamination of soils.
(Information will be provided after completion of DandD Version 2)

Case 2: Limited contamination in a small area near the house.
(Information will be provided after completion of DandD Version 2)

Case 3: General contamination of the garden.
(Information will be provided after completion of DandD Version 2)

Nuclear Fuel Cycle Facilities

These facilities can result in large areas of contamination by a number of long-lived radionuclides. The following examples will exercise and demonstrate the use of DandD for these applications.

Case 1: Natural uranium contamination in fuel fabrication.
(Information will be provided after completion of DandD Version 2)

Case 2: Wide-spread Th-230 and Ra-226 contamination.
(Information will be provided after completion of DandD Version 2)

6.3.6 Generic Description RESRAD/RESRAD-BUILD Deterministic Codes, Development of Probabilistic RESRAD/RESRAD-BUILD Codes, and Examples of Codes Application: .

6.3.6.1 Generic Description of deterministic RESRAD & RESRAD-BUILD Codes:

The deterministic RESRAD and RESRAD-BUILD computer codes were developed by Argonne National Laboratory (ANL) under the sponsorship of the U.S. Department of Energy (DOE). These two codes are pathway analysis models designed to evaluate potential radiological doses to an average member of the specific critical group. RESRAD code uses a residential farmer scenario (Yu et al., 1993) with nearly identical exposure pathways to the DandD residential scenario described in NUREG/CR-5512, Volume 1 (Kennedy and Strenge, 1992). The RESRAD-BUILD code uses a building occupancy scenario which covers all

exposure pathways of the DandD building occupancy scenario plus pathways corresponding external exposure due to air submersion, external exposure due to deposited material, and ingestion of deposited material. A brief description of RESRAD and RESRAD-BUILD codes and conceptual models was presented in Sections 2 and 5. For detailed descriptions of these two deterministic codes the reader is referred to Yu et al. (1993) and Yu et al. (1994). The two deterministic codes were widely used by NRC staff and licensees to estimate doses from radioactively contaminated sites and structures. These two codes were selected because they possess the following attributes:

- the software has been widely accepted and there is already a larger user base,
- the models in the software were designed and have been applied successfully, to more complex physical and contamination conditions than DandD code, and
- verification and validation of these two codes are well documented (Yu, 1999; NRC, 1998c).

It should be noted that RESRAD code has been widely used tested by national and international agencies and has gone through verification (HNUS, 1994) and dose model comparison (Haaker et al., 1999; EPRI, 1999) and benchmarked (DOE, 1995). Therefore, RESRAD and RESRAD-BUILD codes were continuously developed and updated with new code versions. The latest deterministic code versions that were available before development of probabilistic codes was RESRAD 5.91 and RESRAD-BUILD 2.82.

6.3.6.2 Development of Probabilistic RESRAD & RESRAD-BUILD Codes:

The NRC has adopted the risk-informed approach in assessing impacts on the health and safety of the public from radioactive contamination. Therefore, the NRC tasked ANL to develop parameter distribution functions and parametric analysis for these commonly used codes. RESRAD 5.91 and RESRAD-BUILD 2.82 versions were frozen for development of the probabilistic codes. Therefore, ANL was tasked to develop necessary computer modules for conducting probabilistic dose analysis. As part of this effort, external modules equipped with probabilistic sampling and analytical capabilities have been developed for RESRAD and RESRAD-BUILD codes. The modules are also equipped with user-friendly input/output interface features to accommodate numerous parameter distribution functions and results display requirements. The code and the interface modules have been designed to operate on the Microsoft Windows™ 95, 98, and NT platforms. The newly developed RESRAD version is 6.0 and RESRAD-BUILD is 3.0. Probabilistic parametric data distributions were developed through the following steps:

Step 1: Parameter Characterization

The parameters were classified relative to its physical, behavioral, or metabolic attributes. A parameter that would depend on the receptor's behavior and the scenario definition was classified as a behavioral parameter. A parameter representing a metabolic characteristic which is independent of the scenario is classified as a metabolic parameter. Any parameter that depends largely on the physical and natural attributes of the site and typically is independent of the receptor behavior and the scenario is considered a physical parameter. .

Step 2: Parameter Ranking

Parameter rankings were classified into three categories: level 1 (high priority), level 2 (medium priority), and level 3 (low priority). These levels of ranking were based on: a) relevance of the parameter in dose calculations, b) variability of the dose as a result of changes in parameter value, c) parameter type (e.g., physical, behavioral, or metabolic), and d) availability of data on the specific parameter. Based on this ranking criteria, 14 parameters were ranked level 1, 59 level 2, and 120 parameters levels 3for both RESRAD and RESRAD-BUILD codes.

Step 3: Parameter Distribution

Parameter distributions were developed for all 73 parameters of levels 1 and 2 and for very few of level 3 parameters. The data were obtained from published information and data representative of a national distribution, Correlations among parameters was also studied. For the parameter distribution analysis, the residential farmer and the building occupancy scenarios were used for RESRAD and RESRAD-BUILD codes respectively. These two scenarios serve as baseline to this analytical process. For RESRAD code, the peak TEDE dose to the average member of the critical group within 1000 years was used. For RESRAD-BUILD code, the initial dose (e.g., at time 0) was assumed.

The probabilistic analysis was performed by using the stratified sampling of the Latin Hypercube Sampling (LHS) method for collection of input parameter distributions. The LHS method provides an appropriate process for multi-parameter sampling. The dose estimates are generated at different quantile values (e.g., 50^{th} or 90^{th} percentile). The spread of dose was identified by the ratio of dose at 99^{th} to the dose at the 50^{th} percentile for the residential scenario and by the ratio of dose at the 95^{th} percentile to the 50^{th} percentile for the building occupancy scenario. Regression analysis was used to identify sensitive parameters . For example, the partial rank correlation coefficients (PRCC) and the standardized rank regression coefficients (SRCC), were used in the residential and building occupancy scenarios respectively. The effects of sensitive parameters on the dose distributions were studied for the radionuclides Am-241, C-14, Co-60, Cs-137, H-3, Pu-239, Ra-226, Sr-90, Th-230, and U-238. These radionuclides were selected because they include all pathways and are common for decommissioning facilities. The

sensitivities of site-specific parameters on source area and thickness were also analyzed for RESRAD with sources: a) area of 100 m2 and thickness of 15 cm, b) area of 2,400 m2 and thickness of 15 cm., and c) area of 10,000 m2 and thickness of 2 m. For RESRAD-BUILD, the both surface and volumetric configurations were selected for source areas 36 m^2, 200 m^2, and 900 m^2. The parameter uncertainty analysis showed that there is no single correlation or regression coefficient (e.g., PRCC, SRCC) that can be used alone to identify generic sensitive parameters for all cases. The coefficients however are useful guides to use in conjunction with other aids (e.g., scatter plots and/or further analysis) to identify sensitive parameters. Therefore, site-specific distributions and sensitivity analysis should be conducted as much as practicable.

6.3.6.3 Description of Probabilistic Module Used to Evaluate Dose Distribution

Integration with RESRAD Codes

The probabilistic module is integrated into both the RESRAD and RESRAD-BUILD software packages. The system has been designed so that the details of file, data, and calculation modules are hidden from the user. The high-level details of this system are shown in Figure C6.1. The user can start the programs, specify cases, and run the codes in a manner similar to the previous versions. The probabilistic module input is displayed through either the toolbar or by pressing the “F8" key when the windows focus is on a specific parameter. The output module is displayed through the menu. (See Figure C6.2 for a diagram of this process). Figure C6.1 shows a diagram illustrating integration of probabilistic modules with RESRAD and RESRAD-BUILD codes.

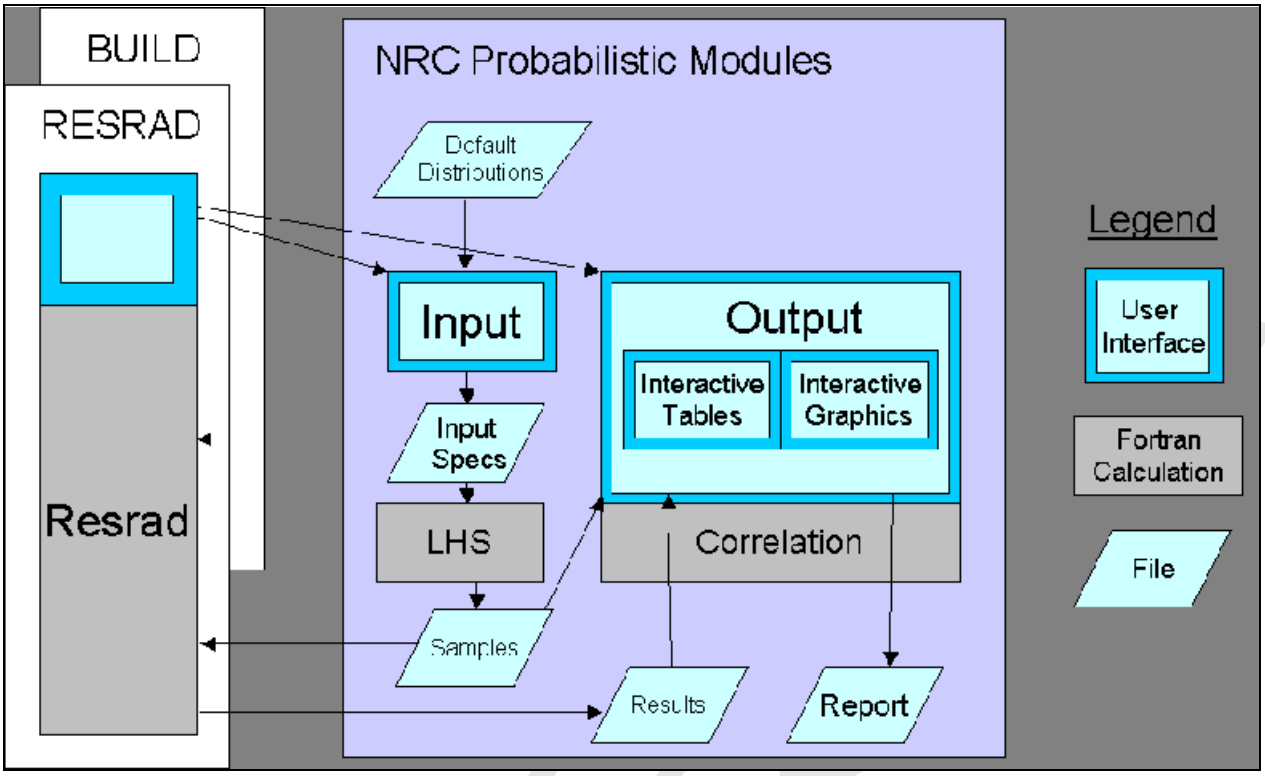

Figure C6.1 Integration of Probabilistic Modules with RESRAD/RESRAD-BUILD Codes.

Procedure for Code Navigation

The procedures for using the probabilistic analysis module are as follows:

- Users run the standard software interface (i.e. RESRAD or RESRAD-BUILD) to set deterministic values for parameters not involved with probabilistic analysis.
- Probabilistic analysis is set by finding parameters in the standard interface and pressing the "F8" key. The probabilistic input window with four tab screens will appear. The parameter will be automatically added, with its default distribution, to the list of parameters for probabilistic analysis.
- If the probabilistic analysis is activated, after running the standard software the probabilistic runs will begin.
- After completion of the calculations, the interactive output window will appear so tables and graphics can be created to display results. Access is available to both the textual report and the detailed data dump files.

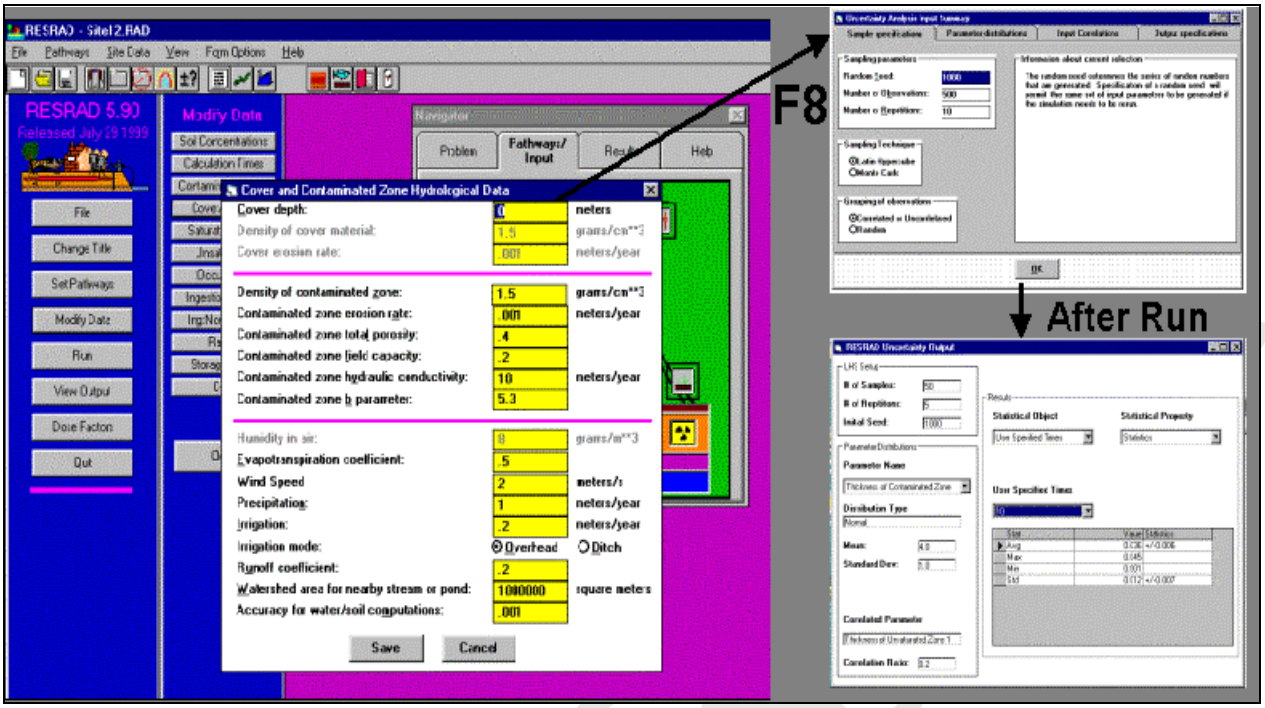

Figure C6.2 Diagram Showing User's Access from RESRAD Interface (left) to Probabilistic Input Window (upper right) and Probabilistic Output Window (lower right).

The probabilistic modules have been designed to be flexible and quite independent of the original RESRAD or RESRAD-BUILD application, yet easily applied and integrated with the application and utilizing previously written software for Latin Hypercube sampling (LHS) and correlation analysis.

The input window (see Section A.3) takes information from the default distribution database and from user's commands to construct the list of parameters, their distributions and correlations, and general sampling options. At run time, the LHS code is activated to perform the sampling. The code is then run on these samples, and the results are stored for incorporation into textual reports.

6.3.6.4 Input Windows

Sample Specifications

The user is allowed to specify details of the sample generation (Figure C6.3). Included in this specification are the beginning random seed, the number of observations and repetitions, the sampling technique, and the grouping of observations. Detailed information about these options is displayed on the right-hand side of this window as the user navigates through the options. Usually the user will be concerned with the number of observations and repetitions.

Sampling Technique

The LHS option will split the distribution to be sampled into a number of equally probable distribution segments (the number is equal to the desired number of observations) and will obtain one sample at random from within each segment. This procedure ensures that the samples cover the entire range of the distribution. The Monte Carlo option will obtain each of the specified number of samples randomly from within the whole distribution.

Grouping of Observations

Correlated or uncorrelated grouping will order the samples for each variable so that (1) the correlations between the specified variables are as close as possible to the specified input correlations, and (2) the correlations between the variables that are not specified to be correlated will be as close to zero as possible. Random grouping will group the variables in the order that they were obtained. It is possible that some of the variables so sampled will be correlated just by chance.

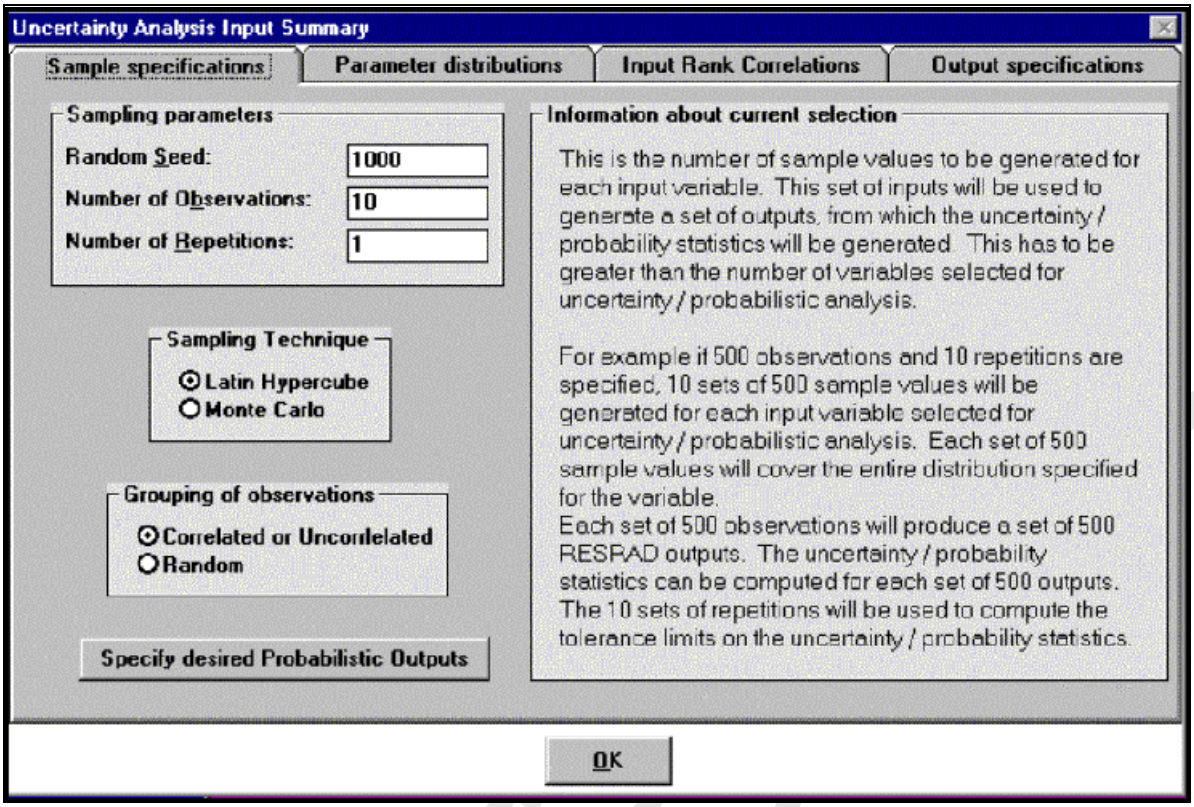

Figure C6.3 Probabilistic Analysis Sample Specification.

Parameter Distributions

The parameter distribution tab screen allows the user to view and edit all currently specified parameter distributions for probabilistic analysis (Figure C6.4). The parameters are listed in the left frame. The detailed distribution properties are shown in the right frame.

Navigation

Navigation to other parameter distributions is achieved by either clicking on the parameter on the left side or using the “Up-Down” arrow control on the left side.

Parameter List for Probabilistic Analysis

The list of the currently chosen parameters is shown on the left in a three-column table displaying the variable description, variable name in the code, and the distribution type. If the use clicks on any element in the row, complete distribution properties for the variable will appear for review and edit on the right.

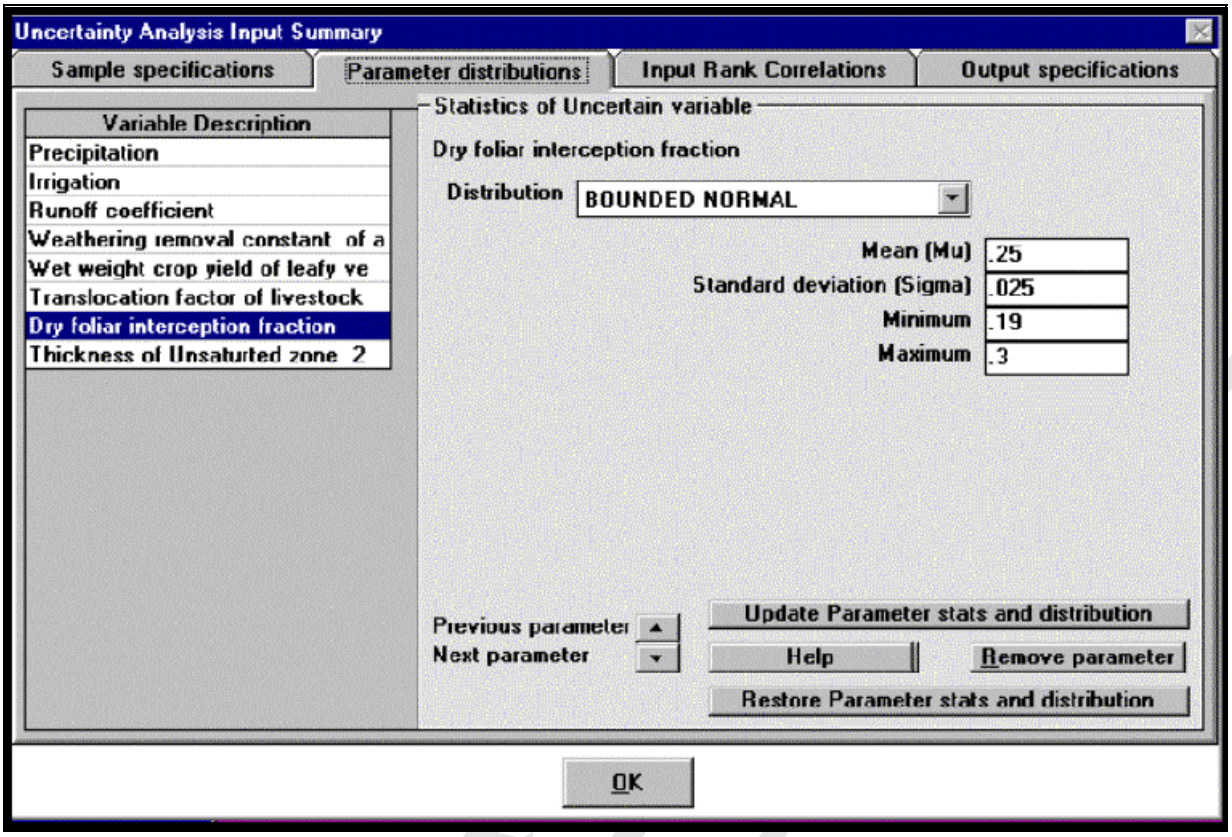

Figure C6.4 Specified Parameter Distributions for Probabilistic Analysis.

Statistics of Uncertain Variable

The properties involved are the distribution type, shape parameters concerning the specific distribution type, and upper and lower truncation bounds. In this particular example, the shape parameters are for the normal distribution, that is, the mean and standard deviation. If the user wishes to accept the default distribution for this parameter, the "Default for assumptions" can be selected. These assumptions also include those specified on the "Sample Specification" tab that are beyond the input specifications of the deterministic RESRAD codes. The user can also remove the parameter from further probabilistic consideration by clicking the "Remove Parameter" button.

Input Rank Correlations

The input correlations tab screen allows the user to view and edit all correlations between input parameters for probabilistic analysis (Figure C6.5). The paired parameters with non-zero correlations are listed in the left frame. Correlations can be modified, added, or deleted in the right frame.

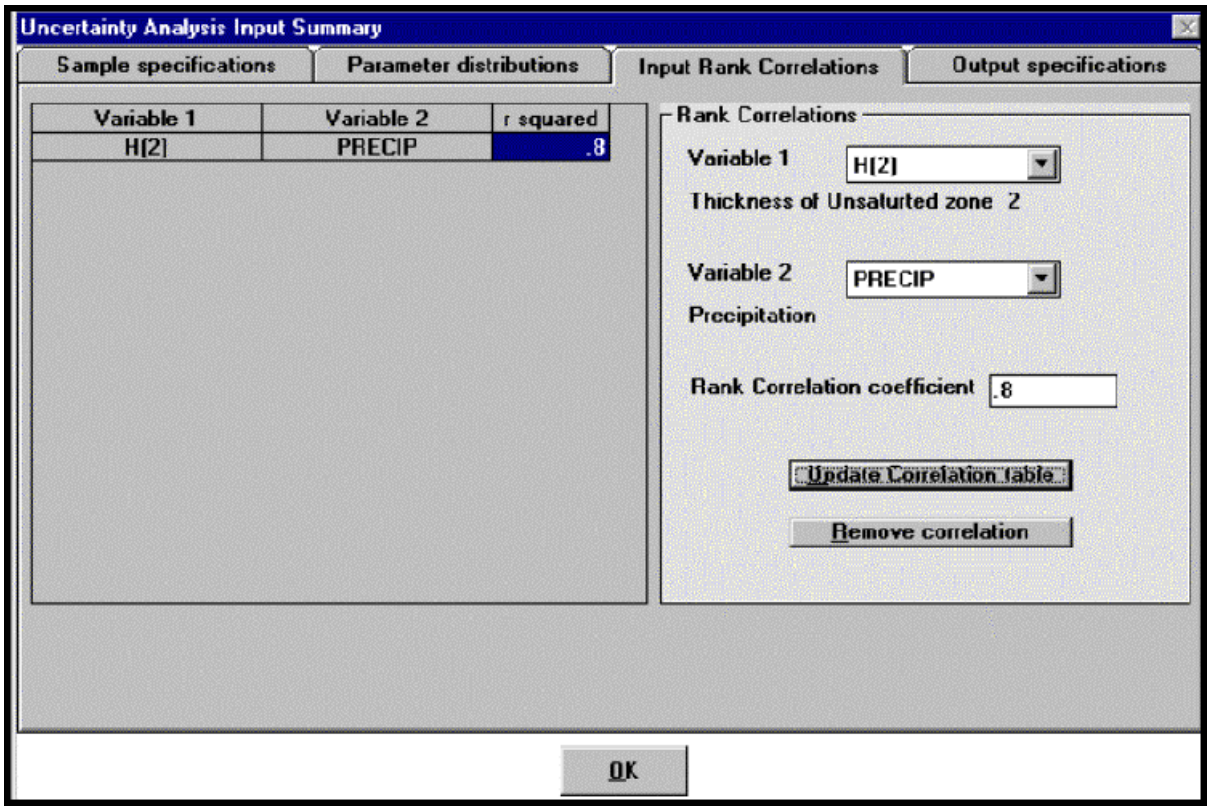

Figure C6.5 Specified Input Rank Correlation for Probabilistic Analysis.

Navigation

The user can select an existing correlation pair by clicking on its row in the left frame. New pairs are chosen on the right side by selecting the two variables. The edits in this frame are incorporated after clicking the "Update Correlation Table" button. The pair is removed by selecting the "Remove Correlation" button.

Parameter List for Correlation

The currently chosen pairs of parameters are listed in the left frame in a three-column table that shows the variable names in the code and the correlation coefficient. If the user clicks on any element in any row of the table, the correlation can be modified or deleted in the right frame. The range of correlation coefficient is –1.00 to 1.00. The correlation for all pairs not specified here is assumed to be 0.0. The user can check the results of the sampling correlation after the run has been completed. Full descriptions of the variables can be seen in the right frame. If more parameters are chosen for correlation than fit in the window, the left side becomes a scrolling table.

Correlation Edit

The two parameters in the correlation and the correlation coefficient are shown and editable in the right frame. The user can also remove the parameter from further probabilistic consideration by clicking the "Remove Correlation" button.

6.3.7 Use of codes and models other than DandD and RESRAD:

Staff should provide flexibility for possible use of other codes and models selected by users. However, less common codes specifically those developed by users, may require more extensive staff review and verifications. In this context staff may conduct review of the following aspects pertaining when using other less common codes:

a) scope of code application and applicability to the concerned site

b) extensive review of the generic code selection criteria listed in 6.3.1

c) review of the mathematical formulation of the associated models and the selected dose conversion factors

d) review of the conceptual model, including source-term model, used in the code and compatibility with site conditions

e) review of code performance and comparison with commonly used and verified codes

f) review of code capability regarding handling of default pathways and consistency in selection of default parameters (e.g., occupancy, behavioral, and metabolic parameters)

g) detailed review of codes/models documentation and updates for code/model modifications including QA/QC reviews.

6.3.8 Modeling of complex sites:

Complex sites refers to sites with any of the following contamination conditions or combination of one or more of these conditions:

a) sites with existing groundwater/surface water contamination

b) sites with diversified and extensive surface/subsurface contamination that may require modeling of multiple sources at the site with potential impact of one source over another

c) Sites with current off-site releases such that alternate offsite scenario(s) may be required or use of onsite resident farmer scenario may be inadequate (e.g., sites with multiple receptors)

d) Sites with physical barriers or vaults

e) Sites with unusual physical or lithologic properties such as highly fractured formation, karst features, or with sinkholes that may significantly impact assumptions of transport models or the overall conceptual model.

Complex sites may require more advanced performance assessment modeling and analysis specifically regarding selection of appropriate models/codes, characterization data needed to support the models selected, source-term assumptions, and internal consistencies in the associated transport models. Due to the complex nature these sites, staff review depend on site-specific conditions and degree of site complexity. Therefore, a generic staff review of complex sites cannot be articulated in the current SRP. Licensees and staff need interact early for information and directions regarding development of a proper decommissioning plan. In other words, staff may tailor a decommissioning review plan based on actual conditions of the complex site based on early interaction between NRC staff and the licensee.

7.0 Criteria for Selecting or Modifying Input Parameter Values

7.1 Introduction

Any analytical approach to dose assessment will involve the selection of appropriate values for input parameters. Each computer modeling code or other analytical methods that a licensee may use will have its own suite of input parameters. Also, unless the licensee is performing a screening analysis, each site or facility (hereafter referred to collectively as "site") will likely have its own defining characteristics that must be incorporated into the dose assessment through the selection of input parameter values.

This section provides general guidelines for the reviewer to consider in evaluating a licensee's selection of values for input parameters. Three aspects of parameter value selection are addressed:

- Selection of parameter values or range of values
- Technical justification to support value selection
- Evaluation of the impact of parameter selection on dose assessment results

Section 7.2 addresses several general issues related to parameter value selection that should be considered by a reviewer. Section 7.3 presents default input parameter data sets for DandD and RESRAD, and discusses the development of data sets for other computer codes and analytical tools. Section 7.4 presents several approaches to modifying the DandD and RESRAD parameter sets for site-specific analyses. (For clarity, all tables are provided at the end of the section.)

7.2 Issues in Modifying Parameters

In addressing the three aspects of parameter value selection identified above, several issues should be discussed. First is the distinction between screening analysis and site-specific analysis, with respect to parameter value modification. Second is the appropriateness of accepting default input parameter values in site-specific analyses. Third is the level of justification expected to support the selection of site-specific input parameter values. The reviewer should consider these issues in evaluating a licensee's dose assessment.

7.2.1 Screening Analyses versus Site-specific Analyses

A licensee may perform a screening analysis to demonstrate compliance with the radiological criteria for license termination specified in 10 CFR Part 20, Subpart E. The screening analysis, described in Section 2 of this document, requires that the licensee either (1) refer to radionuclide-specific screening values listed in the Federal Register (63 FR 64132 and 64 FR 68395), or (2) use the DandD computer code. A licensee pursuing the screening option may find that implementation of the DandD code is necessary if radionuclides not included in the Federal Register listings must be considered.

The reviewer should ensure that a licensee performing a screening analysis using the DandD code limits parameter modification to identifying radionuclides of interest and specifying the radionuclide

concentrations. The reviewer should verify that the licensee has not modified any other input parameter values. The output file generated by DandD identifies all parameter values that have been modified. Modifying any input parameter value from a default value will constitute a site-specific analysis. The default "screening" input parameter data for DandD is provided for reference in Section 7.3. Modification of the default parameter set for site-specific analysis is discussed in Section 7.4

7.2.2 Default Values Versus Site-specific Values

DandD and many other computer codes used for dose assessment provide the user with default values for the input parameters. Often, the user only needs to select radionuclides to execute the code. This allows the user to quickly obtain results with very little time expended in developing input data sets.

This has several obvious and significant drawbacks. A typical user of a computer code gains an understanding and appreciation of the conceptual and numerical modeling approaches of a code through the process of developing data input sets. If default parameter values are not available, the user must address each and every input parameter, determine what characteristics of the modeled system the parameter represents and how the parameter is used in the code, and develop a value for the input parameter that is reasonable and appropriate for both the system being modeled and for the conceptual and numerical models implemented by the code. The availability of default values for input parameters could result in the user performing a "site-specific" analysis to modify values for parameters for which site data are readily available and accept the default values as appropriate for the remaining parameters, without an adequate understanding of the parameters and the implications of accepting the default values.

On the other hand, utilizing default values that have been reviewed by the NRC staff and considered appropriate for dose assessments supporting decommissioning (1) promotes consistency among analyses (where appropriate), (2) focuses licensee and NRC staff resources on parameters considered significant with respect to the dose assessment results, and (3) facilitates review of the licensee's dose assessment by the NRC staff.

To benefit from the advantages while minimizing the disadvantages, the reviewer should ensure that the licensee employs default parameter values in a manner consistent with the guidance provided in this section.

7.2.3 Justifying Site-specific Parameter Values

A reviewer should evaluate whether a licensee submitting a site-specific dose assessment has demonstrated that all parameter input values are appropriate for the site being modeled. However, this does not require the licensee to submit a detailed analysis to support the values selected for each and every input parameter. Instead, the level of justification required should be based on the parameter classification and should be commensurate with the significance of the parameter relative to the dose assessment results, as evaluated through sensitivity analyses. The sensitivity analyses will reflect the relative significance of exposure pathways. Note that the relative

significance of exposure pathways may change as parameters are modified. Methods for performing sensitivity analyses are discussed in Section 8.

Dose assessment input parameters may be generally classified as behavioral, metabolic or physical. Behavioral parameters (B) collectively describe the receptor, the exposed individual for which the dose received is being assessed. The values selected for these input parameters will depend on the behavior hypothesized for the exposed individual. Metabolic parameters (M) also describe the exposed individual, but generally address involuntary characteristics of the individual. Physical parameters (P) collectively describe the physical characteristics of the site being modeled. These would include the geohydrological, geochemical and meteorological characteristics of the site. The characteristics of atmospheric and biospheric transport up to, but not including, uptake by or exposure of the dose receptor would also be considered physical input parameters.

There is always uncertainty associated with the behavior of a hypothetical receptor. For this reason, the licensee may accept a generically defined receptor for their analysis. The generically defined receptor is the “average member of the critical group”. The characteristics of this exposed individual and the criteria for modifying the characteristics for a site-specific analysis are discussed in Section 4. The licensee may use default values for the behavioral and metabolic parameters with limited justification if the values are consistent with the generic definition of the average member of the critical group and the screening group is reflective of the scenario.

The reviewer should verify that the licensee has used site-specific values for all physical parameters related to geohydrologic conditions. “Site-specific” in this context includes (1) information directly related to the site, (2) information characterizing the region that is consistent with site conditions, and (3) generic information that is consistent with the specific geohydrologic conditions at the site (e.g., consistent with the surface soil unsaturated zone soil classifications). The justification for site-specific physical parameter values should demonstrate that the site-specific values selected are not inconsistent with the known or expected characteristics of the physical site being modeled. The level of justification should be based on the significance of the parameter to the results of the dose assessment. The licensee should evaluate the significance through sensitivity analyses (see Section 8). If a licensee relies on the DandD default values for the physical parameters describing geochemical conditions (i.e., partition coefficients) and biosphere transport (e.g., crop yields, soil-to-plant concentration factors), the reviewer should evaluate whether the default parameters are inconsistent with known or expected conditions at the site.

7.3 Input parameter data sets

7.3.1 DandD default probabilistic parameter set

Probabilistic analyses using the DandD computer code were performed to establish the screening values for building and surface-soil contamination that were published in the Federal Register in November 1998 and December 1999 (63 FR 64132 and 64 FR 68395). In performing these screening analyses, data were compiled for over 600 input parameters and reviewed by the NRC staff. These data are discussed in great detail in NUREG/CR-5512, Volume 3, and are directly

incorporated into DandD (starting with Version 2). These data form the reference input parameter set for probabilistic analyses using DandD.

The DandD computer code may be used to evaluate radiological doses for two exposure scenarios: (1) the building occupancy scenario and (2) the residential scenario. These exposure scenarios and the associated exposure pathways are discussed in detail in Section 4.

Table C7.1 identifies the input parameters required to analyze the DandD building occupancy scenario. Table C7.1 provides the parameter symbol and name, the dimensional units, and a brief description. The fourth column of Table C7.1 indicates whether each parameter is considered to address a behavioral, metabolic or physical characteristic. This parameter classification is defined in NUREG/CR-5512, Volume 3:

- Behavioral parameters (B) characterize the average member of the critical group -- the group of individuals reasonably expected to receive the greatest exposure to residual radioactivity for any applicable set of circumstances (10 CFR 20.1003).

- Metabolic parameters (M) characterize the metabolic functioning of the average member of the critical group. Volumetric breathing rates are the only metabolic parameters used in DandD. (Dose conversion factors, while considered metabolic, are not modified by the DandD user.)

- Physical parameters (P) describe characteristics of the physical site. The values assigned to the physical parameters depend on the physical characteristics of the site and are generally independent of the characteristics of the average member of the critical group.

Detailed discussion of this classification is provided in NUREG/CR-5512, Volume 3. The fifth column indicates whether the default value assigned to the parameter is a constant value, a derived value (i.e., a function of other input parameters), or a probability distribution function from which a value is sampled with each calculational iteration of the code. For constant parameters, the default value is provided. For parameters characterized by a distribution, the values defining the distribution are provided. The DandD distribution types and distribution parameters are provided in Table C7.2.

For the residential scenario, DandD requires values for over 250 general input parameters and over 300 element-specific parameters. The general input parameters are identified in Table C7.3. For each parameter associated with the residential scenario, the information presented in Table C7.3 is the same as that described in the preceding paragraph for Table C7.1. Information is not provided here for the element-specific parameters:

- Partition coefficients
- Soil-to-plant transfer factors - leafy
- Soil-to-plant transfer factors - root
- Soil-to-plant transfer factors - fruit
- Soil-to-plant transfer factors - grain
- Animal transfer factor - beef

- Animal transfer factor - poultry
- Animal transfer factor - milk
- Animal transfer factor - eggs
- Bioaccumulation factor - fish

Instead, the reader is referred to NUREG/CR-5512, Volume 3 and the current version of the DandD computer code.

7.3.2 DandD default deterministic parameter set

Several default parameter sets have been developed to support deterministic analyses with the DandD code. NUREG/CR-5512, Volume 1, initially presented the conceptual and mathematical foundation of the DandD code, and deterministic values for many input parameters were presented in the document. Volume 3 of NUREG/CR-5512 incorporated much of the parameter information from Volume 1 in developing the default probabilistic input parameter set, making corrections and updating values as necessary. Therefore, a licensee should not refer to NUREG/CR-5512, Volume 1, as a primary source for a default deterministic parameter set.

Similarly, DandD Version 1, which did not support probabilistic analyses, provided a default deterministic input parameter set. DandD Version 2 has replaced Version 1, the DandD Version 1 default parameter set should not be used as a reference data set.

A user may perform deterministic analyses using DandD (Version 2 or later). This would require the user to change all parameter distribution types to “constant” and specify a single value. However, the NRC does not intend to provide a default deterministic input parameter set to be used in conjunction with DandD. Also, a licensee intending to support decommissioning activities with deterministic dose assessments should ensure that the deterministic approach will provide the information necessary to demonstrate compliance (e.g., support necessary sensitivity analyses as described in Section 8).

7.3.3 RESRAD default probabilistic parameter set

The most recent versions of the RESRAD and RESRAD-BUILD computer codes include the option to perform probabilistic dose assessments. The RESRAD team at Argonne National Laboratory worked with NRC staff to develop a default input parameter set that may be used to perform probabilistic dose assessments with the RESRAD and RESRAD-BUILD codes. These default probabilistic input parameter sets are documented in *Parameter Distributions for Use in RESRAD and RESRAD-BUILD Computer Codes* (Biwer et al., 2000).

Table C7.4 identifies the default probabilistic parameter set for the RESRAD-BUILD code. The table identifies each RESRAD-BUILD input parameter and associated dimensional units, and provides the parameter classification (B, M or P). If two classification codes are provided, the first is considered the primary classification. Table C7.4 then provides the default parameter distribution type, and the values for the distribution’s statistical parameters.

Table C7.5 identifies the type of parameter distributions available in the RESRAD and RESRAD-BUILD codes to characterize the RESRAD and RESRAD-BUILD input parameters. Table C7.5 also identifies the input variable necessary to define each distribution type. The parameter distributions are discussed in detail in Appendix A of Biwer et al. (2000).

Table C7.6 identifies the default probabilistic parameter set for the RESRAD code. For each RESRAD input parameter, Table C7.6 provides the same information as that provided for RESRAD-BUILD, as described in the preceding paragraph.

Table C7.6 does not provide the default parameter distributions for the element-specific parameters required by RESRAD:

- Distribution coefficients for the contaminated zone
- Distribution coefficients for the unsaturated zone
- Distribution coefficients for the saturated zone
- Transfer factors for plants
- Transfer factors for milk
- Transfer factors for meat
- Bioaccumulation factors for fish

This information is provided in Biwer et al. (2000). Also, Table C7.4 and C7.6 do not provide the default values for parameters for which probabilistic parameters were not developed through Biwer et al. (2000). All RESRAD and RESRAD-BUILD parameters were evaluated and a subset was identified for probabilistic evaluation, as documented in *Selection of RESRAD and RESRAD-BUILD Input Parameters for Detailed Distribution Analysis* (Cheng et al., 1999).

7.3.4 RESRAD default deterministic parameter set

Versions of RESRAD (e.g., Versions 5.82, 5.91 and 5.95) and RESRAD-BUILD (Version 2.37) include default parameter values which support the RESRAD and RESRAD-BUILD deterministic analyses. Many of these default parameters are documented in *Data Collection Handbook to Support Modeling the Impacts of Radioactive Material in Soil* (Yu et al., 1993a). As a set, these are not considered to be acceptable default input parameter values for performing dose assessments in support of decommissioning. Instead, a licensee may use the parameter set described in the preceding section as a starting point for their analyses. The reviewer should ensure that a licensee justifies the selected values and that the values are consistent with existing or expected conditions at the site.

7.3.5 Input data sets for other computer codes

A licensee may choose to use a computer code or analytical approach other than DandD or RESRAD/RESRAD-BUILD to perform the dose assessment in support of decommissioning (see Section 6). Each code or analytical approach will have a unique set of input parameters.

However, there will likely be some input parameters that are also included in the DandD input parameter set.

The reviewer should verify that a licensee provides a listing of all input parameters required in their analysis. For each parameter, the licensee should provide a discussion similar to that provided in NUREG/CR-5512, Volume 3, Chapters 5 and 6. The discussion should include the parameter name, a description of the parameter, a discussion of how the parameter is used in the dose assessment model, and the licensee's classification of the input parameter (i.e., behavioral, metabolic or physical). For the parameters being represented by constant values, the licensee should provide the range of appropriate values for the parameter, the single value selected for the parameter, and the basis for the range and selected value, including references. The level of justification to be provided in the basis will be based on the classification of the parameter (i.e., behavioral, metabolic or physical) and the relative significance of the parameter in the dose assessment.

For input parameters classified as "behavioral" or "metabolic", the reviewer should verify that the licensee specifies values that are consistent with the default screening values specified for the DandD behavioral and metabolic parameters (Tables C7.1 and C7.3), as long as the definition of the critical group has not been modified (see Section 4). Consistency will depend upon the conceptual and numerical models underlying the code being used and the manner in which the parameters are used in the models. Using consistent behavioral and metabolic parameter values for the default critical group will support a relatively standardized definition of the "average member of the critical group" among analyses. The basis the licensee provides for these parameters should identify the comparable DandD parameters and discuss any adjustments necessary to accommodate differences between DandD and the code or analytical method being used.

For the input parameters the licensee classifies as physical, other than those related to geochemical conditions and atmospheric and biospheric transport, the reviewer should verify that the licensee uses site-specific values whenever available. The licensee should provide the soil classification for all soil units and specify consistent values for all geohydrologic parameters. For geochemical parameters, such as partition coefficients, the licensee may rely on DandD default probabilistic values, as long as justification is provided to demonstrate that the values are not inconsistent with geochemical conditions at the site. Site conditions may require that the licensee modify the default parameters to ensure consistency. Additionally, it is important to note that the distributions may not be applicable to codes other than DandD. For meteorological parameters, the licensee should use values that are based on applicable site or regional data. For physical parameters related to atmospheric and biospheric transport, the licensee may accept DandD default values with minimal justification, using NUREG/CR-5512, Volume 3, as a starting reference point. Physical parameters related to biosphere transport would include parameters such as crop yields, animal ingestion rates, transfer factors, and crop growing times. The reviewer should evaluate whether the justification provided by the licensee demonstrates that the default values are not inconsistent with conditions at the site.

7.4. Recommended Approach to Parameter Modification

Any analysis that does not meet the conditions of a screening analysis will be considered a site-specific analysis. This will include all analyses using the DandD computer code where one or more input parameters values have been modified from default values, as well as analyses using analytical methods or computer codes other than DandD.

7.4.1 Modifying the DandD default probabilistic parameter set

A reviewer should expect that a licensee who is modifying parameter values for a site-specific analysis using DandD is cognizant of the following:

- What the parameter represents
- How the parameter is used in the DandD code
- The basis for the default parameter value
- Which parameters are physically or numerically correlated

Tables C7.1 and C7.3 identify the DandD input parameters and default distribution types and values. NUREG/CR-5512, Volumes 1 through 3 describes in detail what each parameter is intended to represent. Volume 1 provides the original parameter definitions. Volume 1 also provides the mathematical formulations underlying the DandD code which will allow the user to (1) understand how each parameter is used and the implication of parameter modification on the resulting calculated dose and (2) identify numerical correlations among parameters. Volume 2 (the DandD user's manual) redefines several of the input parameters and mathematical formulations based on implementation of the Volume 1 methodology in the DandD computer code. Finally, Volume 3 provides a detailed discussion of most input parameters, allowing the user to fully understand the basis for the default values. Volume 3 provides a parameter description and a discussion of how parameters are used in the code, a review of the information sources on which the default values are based, a discussion of uncertainty in the default parameter values, and insight into the selection of alternative parameter values. The DandD user performing site-specific analyses with DandD should be cognizant of the information provided in the three volumes of NUREG/CR-5512.

A licensee may modify DandD behavioral (B) and metabolic (M) input parameter values for the building occupancy and residential scenarios to reflect the characteristics of the average member of a *site-specific* critical group. NUREG/CR-5512, Volume 3, provides the basis for the default value for each behavioral and metabolic parameter. If the licensee modifies the values for these parameters, the reviewer should verify that the licensee has defined a *site-specific* critical group, as discussed in Section 4 of this appendix. The licensee may provide site-specific parameter distributions that reflect the variability of the behavior of the average member of the site-specific critical group, or the licensee may use the mean of the site-specific information as a constant-value input for these parameters, consistent with the concept of the "average member" of the critical group. The justification required to support modification of behavioral and metabolic parameter values should be consistent with the information presented in Section 4.

For the DandD building occupancy scenario, there are only three physical parameters: the resuspension factor (Rfo*), which is derived from the loose fraction (Fl) and the loose resuspension factor (Rfo). Default values for these parameters are given in Table C7.1. Unless the licensee has

site-specific information to indicate that the default values are inconsistent with the default values, the reviewer should verify that the licensee has used the default values for these physical parameters in their calculations.

There are many more physical parameters for the DandD residential scenario (Table C7.3). The physical parameters may be considered in several groups. The following physical parameters address the geohydrologic conditions:

Unsaturated Zone Thickness (H2)	CONTINUOUS LINEAR
Soil Classification (SCSST)	DISCRETE CUMULATIVE
Porosity Probability (NDEV)	UNIFORM (0 to 1)
Permeability Probability (KSDEV)	UNIFORM (0 to 1)
Parameter "b" Probability (BDEV)	UNIFORM (0 to 1)
Water Application Rate (AP)	CONTINUOUS LINEAR
Surface Soil Porosity (N1)	DERIVED
Unsaturated Zone Porosity (N2)	DERIVED
Surface Soil Saturation (F1)	DERIVED
Unsaturated Zone Saturation (F2)	DERIVED
Infiltration Rate (INFIL)	DERIVED
Surface Soil Density (RHO1)	DERIVED
Unsaturated Zone Density (RHO2)	DERIVED
Surface Soil Permeability (Ksat1)	DERIVED
Soil Moisture Content (sh)	DERIVED

For these physical parameters, the licensee should use site-specific distributions and values. (As stated previously, “site-specific” in this context includes (1) information directly related to the site, (2) information characterizing the region that is consistent with site conditions, and (3) generic information that is consistent with the specific geohydrologic conditions at the site (e.g., consistent with the unsaturated zone soil classification)).

The reviewer should verify that the licensee has provided site-specific information for the thickness of the unsaturated zone and the soil classification. In addition, the licensee should ensure that the water application rate is consistent with the irrigation rate (behavioral parameter) if the licensee modifies the irrigation rate. Alternatively, the licensee may demonstrate through sensitivity analyses that the dose assessment results are insensitive to these parameters and use the default values.

Values for the derived parameters will be generated internally according to the soil classification indicated and the uniform distributions defined for the porosity probability (NDEV), the permeability probability (KSDEV) and the parameter "b" probability (BDEV). The reviewer should verify that the licensee has not modified the uniform distributions for these three parameters. If site-specific data is available, the licensee may proceed to modify the derived geohydrologic parameters, consistent with the information presented in NUREG/CR-5512, Volume 3.

The only geochemical parameter used in DandD are the element-specific partition coefficient. As documented in NUREG/CR-5512, Volume 3, the partition coefficients at a site are generally

dependent on geochemical conditions and are generally independent of soil classification. If the licensee has used the default distributions, the reviewer should evaluate whether the defaults are inconsistent with known or expected conditions at the site.

The following physical parameters address radionuclide transport through the atmosphere and exposure to direct radiation:

Outdoor Shielding Factor (SFO)	CONSTANT
Flood dust loading (PD)	UNIFORM
Indoor Resuspension Factor (RFR)	LOGUNIFORM
Outdoor Dust Loading (CDO)	LOGUNIFORM
Indoor Dust Loading (CDI)	DERIVED
Indoor/Outdoor Penetration Factor (PF)	UNIFORM
Gardening Dust Loading (CDG)	UNIFORM

The remaining physical parameters address characteristics of transport through the biosphere:

Growing Periods (produce, forage, grain, hay) (TG_(#))	CONSTANT
Animal Product Specific Activity (SATac)	CONSTANT
Livestock Feeding Periods (TF_(#))	CONSTANT
Animal Product Yields (YA(#))	CONSTANT
Interception Fractions (R_(#))	UNIFORM
Translocation factors (T_(#))	CONSTANT
Contaminated Fractions (x_(#))	CONSTANT
Crop Yields (Y_(#))	CONTINUOUS LINEAR
Wet-to-dry conversion factors (W_(#))	CONTINUOUS LINEAR
Animal Ingestion Rates (Q_(#))	BETA
Mass-Loading factors (ML_(#))	CONSTANT
Carbon Fractions (fc_(#))	CONSTANT
Hydrogen Fractions (fh_(#))	CONSTANT
Hydrogen Fraction: Soil (fhd016)	DERIVED
Tritium Equivalence: Plant/Soil (sasvh)	CONSTANT
Tritium Equivalence: Plant/Water (sawvh)	CONSTANT
Tritium Equivalence: Animal Products (satah)	CONSTANT

These two groups of physical parameters describe characteristics of the transport of radionuclides through the atmosphere or biosphere up to the point of ingestion or inhalation by or external exposure to the receptor. The licensee may accept the default values for these parameters as long as the default values are not inconsistent with conditions that may exist at the site in the future. The licensee should review the basis given in NUREG/CR-5512, Volume 3, for the default values to determine whether the basis is inconsistent with conditions hypothesized for the site. If so, the licensee must modify the input values accordingly. The reviewer should ensure that the licensee documents this assessment for each of the physical parameters. Note that modifying several of these parameters (e.g., crop yields, animal product yields) will affect the derived behavioral parameters (e.g., area of land cultivated).

For the physical parameters, the licensee may use representative distributions or values. A representative distribution should take into account spatial and temporal variation of the parameter at the site. A representative distribution, for example, would be a precipitation rate based on the historical precipitation data for the site, if available, or from surrounding defensibly relevant monitoring locations. The arithmetic or geometric mean value is often used in defining a representative distribution. However, the calculation of a mean value should be weighted to account for non-uniform sampling or other non-uniform parameters (e.g., material volume). The licensee is not required to routinely adopt worst-case, bounding, upper- or lower-percentile, or other overly conservative values in defining distributions.

The review of this information will be facilitated if the licensee presents the information in a tabular or list format. The reviewer should verify that the licensee has listed every DandD input parameter with the default screening distributions or value. For those parameters for which the licensee is using site-specific values (e.g., the physical parameters), the licensee should provide the range of plausible values for the site, the selected value, and supporting justification, including references.

7.4.2 Modifying the RESRAD default probabilistic parameter set

A licensee using the RESRAD or RESRAD-BUILD codes may change parameters from the default values to reflect a site-specific critical group or site-specific conditions, or to incorporate site-specific data. As discussed in the preceding section, the reviewer should expect that a licensee who is modifying parameter values for a site-specific analysis using RESRAD or RESRAD-BUILD is cognizant of the following:

- What the parameter represents
- How the parameter is used in the code
- The basis for the default parameter value
- Which parameters are physically or numerically correlated

Tables C7.4 and Table C7.6 identify the RESRAD and RESRAD-BUILD input parameters and default distribution types and values. The licensee should refer to the current code documentation to determine how the parameters are used in the code. References to the documentation should be provided. With respect to the basis for the default parameter distributions and values, the licensee should refer to Biwer et al. (2000).

When modifying parameter distributions and values, the licensee should consider whether the parameters are classified as behavioral, metabolic or physical. For behavioral and metabolic parameters for which probability distributions have been developed, the licensee may adopt the default distribution or the mean of the default distribution, as long as the licensee has not modified the definition of the critical group. For behavioral and metabolic parameter for which distributions have not been developed, the licensee should use values or distributions that are consistent with the DandD default distributions, as applicable.

A licensee may modify behavioral (B) and metabolic (M) default input parameter values to reflect the characteristics of the average member of a *site-specific* critical group. The licensee may modify the values for these parameters if the licensee has defined a *site-specific* critical group, as

discussed in Section 4 of this appendix. The licensee may provide site-specific parameter distributions that reflect the variability of the behavior of the average member of the site-specific critical group, or the licensee may use the mean of the site-specific information as a constant-value input for these parameters, consistent with the concept of the "average member" of the critical group. The justification required to support modification of behavioral and metabolic parameter values should be consistent with the information presented in Section 4.

For the physical parameters, the licensee should use site-specific information for the physical parameters addressing geohydrologic and meteorologic conditions. The level of justification for the parameter values should be based on sensitivity analyses. Alternatively, sensitivity analyses may be used to support the use of default parameters.

For the physical parameters describing geochemical conditions (i.e., distribution coefficients), the licensee should use values that are consistent with the DandD default values, as long as the values are not inconsistent with known or expected site conditions. Justification supporting the values should be based on sensitivity analyses.

For the remaining physical parameters (atmospheric and biospheric transport), the licensee may use values that are consistent with the DandD default values, as applicable, as long as the default values are not inconsistent with known or expected site conditions.

7.4.3 Sensitivity Analyses

The level of justification required to support site-specific parameter values should be commensurate with the sensitivity of the results of the dose assessment to the selected values. Sensitivity analyses are discussed in detail in Section 8.

Table C7.1 Default parameter distributions and values for the DandD building occupancy scenario

Parameter symbol:name	Units	Description	Classification	Distribution
To:Time In Building	(hr/week)	The time in the building during the occupancy period	Behavioral	CONTINUOUS
Tto:Occupancy Period	(days)	The duration of the occupancy exposure period	Behavioral	CONSTANT
Vo:Breathing Rate	(m**3/hr)	The average volumetric breathing rate during building occupancy for an 8-hour work day	Metabolic	CONTINUOUS
RFo*:Resuspension Factor	(1/m)	The resuspension factor during the occupancy period	Physical	DERIVED
GO*:Ingestion Rate	(m2/hr)	The secondary ingestion transfer rate of removable surface activity from building surfaces to the mouth during building occupancy	Behavioral	DERIVED
Tstart:Start Time	(days)	The start time of the scenario in days	Program	CONSTANT
Tend:End Time	(days)	The ending time of the scenario in days	Program	CONSTANT
dt:Time Step Size	(days)	The time step size	Program	CONSTANT
Pstep:Print Step Size	(none)	The time steps for the history file. Doses will be written to the history file every n time steps	Program	CONSTANT
AOExt:External Exposure Area	(m**2)	Minimum surface area to which occupant is exposed via external radiation during occupancy period	Behavioral	CONSTANT
AOInh:Inhalation Exposure Area	(m**2)	Minimum surface area to which occupant is exposed via inhalation during occupancy period	Behavioral	CONSTANT
AOIng:Secondary Ingestion Exposure Area	(m**2)	Minimum surface area to which occupant is exposed via secondary ingestion during occupancy period	Behavioral	CONSTANT
AO:Exposure Area	(m**2)	Minimum surface area to which occupant is exposed during the occupancy period	Behavioral	DERIVED
Fl:Loose Fraction	(none)	Fraction of surface contamination available for resuspension and ingestion	Physical	CONSTANT
Rfo:Loose Resuspension Factor	(1/m)	Resuspension factor for loose contamination	Physical	CONTINUOUS LOGARITHMIC
GO:Loose Ingestion Rate	(m2/hr)	The secondary ingestion transfer rate of loose removable surface activity from building surfaces to the mouth during building occupancy	Behavioral	LOGUNIFORM

Table C7.2 DandD Distribution Types and Distribution Parameters

Distribution Type	Distribution Parameters			
FIXED	Value			
NORMAL	Mean	Standard Deviation		
TRUNCATED NORMAL	Mean	Standard Deviation	Lower	Upper
BOUNDED NORMAL	Mean	Standard Deviation	Lower Bound	Upper Bound
NORMAL-B	Value at 0.001	Value at 0.999		
LOGNORMAL	Mean	Error Factor		
LOGNORMAL-N	Mean	Standard Deviation		
TRUNCATED LOGNORMAL	Mean	Error Factor	Lower	Upper
TRUNCATED LOGNORMAL-N	Mean	Standard Deviation	Lower	Upper
BOUNDED LOGNORMAL	Mean	Error Factor	Lower Bound	Upper Bound
BOUNDED LOGNORMAL-N	Mean	Standard Deviation	Lower Bound	Upper Bound
LOGNORMAL-B	Value at 0.001	Value at 0.999		
UNIFORM	A	B		
LOGUNIFORM	A	B		
CONTINUOUS LINEAR	Table of (Value, Probability) pairs			
CONTINUOUS LOGARITHMIC	Table of (Value, Probability) pairs			
CONTINUOUS FREQUENCY	Table of (Value, Probability) pairs			
EXPONENTIAL	lambda			
MAXIMUM ENTROPY	A	mu	B	
WEIBULL	alpha	beta		
PARETO	alpha	beta		
GAMMA	alpha	beta		
BETA	A	B	p	q
INVERSE GAUSSIAN	mu	lambda		
TRIANGULAR	a	b	c	
POISSON	lambda			
BINOMIAL	p	n		
NEGATIVE BINOMIAL	p	n		
GEOMETRIC	p			
HYPERGEOMETRIC	N_N	N_1	N_R	
DISCRETE CUMULATIVE	Table of (Value, Probability) pairs			
DISCRETE HISTOGRAM	Table of (Value, Probability) pairs			

Table C7.3 Default parameter distributions and values for DandD residenatial scenario

Parameter symbol:name	Units	Description	Classification	Distribution	V
Nunsat:Number of Unsaturated Layers	(none)	Number of model layers used to represent the unsaturated zone	Program	CONSTANT	V
TstartR:Start Time	(days)	The start time of the scenario in days	Program	CONSTANT	V
TendR:End Time	(days)	The ending time of the scenario in days	Program	CONSTANT	V
dtR:Time Step Size	(days)	The time step size	Program	CONSTANT	V
PstepR:Print Step Size	(none)	The time steps for the history file. Doses will be written to the file every n time steps	Program	CONSTANT	V
TI:Indoor Exposure Period	(days/year)	The time the resident spends indoors	Behavioral	CONTINUOUS LINEAR	V
					1
					1
					1
					2
					2
					2
					2
					2
					2
					2
					2
					2
					2
					2
					2
					2
					3
TX:Outdoor Exposure Period	(days/year)	The time the resident spends outdoors	Behavioral	CONTINUOUS LINEAR	V
					1
					1
					2
					2
					2
					3
					3
					3
					4
					4
					4
					5
					5
					6
					6
					8
					9
TG:Gardening Period	(days/year)	The time the resident spends gardening	Behavioral	CONTINUOUS LINEAR	V
					0
					0
					0
					0
					0
					0
					1
					1
					1
					2
					3
					5
					7
					8
					1
					1
					1
TTR:Total time in period	(days/year)	Total time in the one year exposure period	Behavioral	CONSTANT	V
SFI:Indoor Shielding Factor	(none)	Shielding factor for the residence	Behavioral	DISCRETE CUMULATIVE	V
					0
					0
					0
					0
SFO:Outdoor Shielding Factor	(none)	Shielding factor for the cover soil	Physical	CONSTANT	V
PD:Flood dust loading	(g/m**2)	Floor dust loading	Physical	UNIFORM	L
					L
RFR:Indoor Resuspension Factor	(1/m)	Resuspension factor for indoor dust	Physical	LOGUNIFORM	L
					L
CDO:Outdoor Dust Loading	(g/m**3)	Average dust loading outdoors	Physical	LOGUNIFORM	L
					L

CDI:Indoor Dust Loading	(g/m**3)	Average dust loading indoors	Physical	DERIVED	
PF:Indoor/Outdoor Penetration Factor	(none)	Fraction of outdoor dust in indoor air	Physical	UNIFORM	L
					L
CDG:Gardening Dust Loading	(g/m**3)	Average dust loading while gardening	Physical	UNIFORM	L
					L
VR:Indoor Breathing Rate	(m**3/hr)	Breathing rate while indoors	Metabolic	CONSTANT	V
VX:Outdoor Breathing Rate	(m**3/hr)	Breathing rate while outdoors	Metabolic	CONSTANT	V
VG:Gardening Breathing Rate	(m**3/hr)	Breathing rate while gardening	Metabolic	CONSTANT	V
GR:Soil Ingestion Transfer Rate	(g/d)	Average rate of soil ingestion	Behavioral	TRIANGULAR	L
					M
					L
H1:Surface Soil Thickness	(m)	Thickness of the surface soil layer	Physical	CONSTANT	V
H2:Unsaturated Zone Thickness	(m)	Thickness of the unsaturated zone	Physical	CONTINUOUS LINEAR	V
					0
					0
					0
					0
					0
					1
					1
					1
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					8
					8
					8
					8
					9
					1
					1
					1
					1
					1
					1
					1
					3
N1:Surface Soil Porosity	(none)	Porosity of the surface soil layer	Physical	DERIVED	
N2:Unsaturated Zone Porosity	(none)	Porosity of the unsaturated zone	Physical	DERIVED	
F1:Surface Soil Saturation	(none)	Saturation ratio of the surface soil layer	Physical	DERIVED	
F2:Unsaturated Zone Saturation	(none)	Saturation ratio of the unsaturated zone	Physical	DERIVED	
INFIL:Infiltration Rate	(m/y)	Net rate of infiltration to aquifer	Physical	DERIVED	
SCSST:Soil Classification	(none)	SCS soil classification ID	Physical	DISCRETE CUMULATIVE	v
					1
					2
					3
					4
					5
					6
					7
					8
					9
					1

					1
					1
NDEV:Porosity Probability	(none)	Relative porosity value within the distribution for this soil type	Physical	UNIFORM	L
					L
KSDEV:Permeability Probability	(none)	Relative permeability value within the distribution for this soil type	Physical	UNIFORM	L
					L
BDEV:Parameter "b" Probability	(none)	Relative value of "b" parameter within the distribution for this soil type	Physical	UNIFORM	L
					L
AP:Water Application Rate	(m/y)	Total water application rate on cultivated area	Physical	CONTINUOUS LINEAR	V
					0
					0
					0
					0
					0
					1
					1
					1
					1
					1
					1
IR:Irrigation Rate	(L/m**2-d)	Annual average irrigation rate	Behavioral	CONTINUOUS LOG	V
					0
					0
					0
					0
					0
					0
					0
					0
					0
					0
					0
					0
					0
					0
					0
					0
					1
					1
					1
					1
					1
					1
					1
					1
					1
					1
					2
					2
					2
					3
					5
					9
RHO1:Surface Soil Density	(g/mL)	Bulk density of soil in the surface soil layer	Physical	DERIVED	
RHO2:Unsaturated Zone Density	(g/mL)	Bulk density of soil in the unsaturated zone	Physical	DERIVED	
Ksat1:Surface Soil Permeabiliy	(cm/sec)	Saturated permeability of the surface soil layer	Physical	DERIVED	
VDR:Volume of Water Consumed	(L)	Volume of water withdrawn for consumptive use	Behavioral	DISCRETE CUMULATIVE	V
					5
					6
					6
					7
					7
					8
					8
					8
					8
					8
					9
					9
					9
					9
					1
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					1
					1
					2
					2
					2
VSW:Volume of Water in Pond	(L)	Volume of water in the pond	Behavioral	CONSTANT	v
AR:Cultivated Area	(m**2)	Area of land cultivated	Behavioral	DERIVED	
TTG:Gardening Period	(days)	Total time in gardening period	Behavioral	CONSTANT	v
TD:Drinking-water consumption period	(days)	Drinking-water consumption period	Behavioral	CONSTANT	v
AREXt:External Exposure Area	(m**2)	Min surf area to which resident is exposed via external rad during resident period	Behavioral	CONSTANT	v
ARInh:Inhalation Exposure Area	(m**2)	Min surf area to which resident is exposed via inhalation during residential period	Behavioral	CONSTANT	v
ARIng:Secondary Ingestion Exposure Area	(m**2)	Min surf area to which resi is exposed via secondary ingestion during resid period	Behavioral	CONSTANT	v
ARAgr:Agricultural Exposure Area	(m**2)	Min surf area to which resid is exposed via any agricultural product during resid period	Behavioral	DERIVED	
ARH2O:Groundwater Exposure Area	(m**2)	Min surf area to which resid is exposed via groundwater during residential period	Behavioral	DERIVED	
ARAll:Exposure Area	(m**2)	Min surf area to which resid is exposed via any pathway during the residential period	Behavioral	DERIVED	
DIET:Garden Diet	(none)	Fraction of human diet grown onsite	Behavioral	CONSTANT	v
Uv(1):Diet - Leafy	(kg/y)	Yearly human consumption of leafy vegetables	Behavioral	CONTINUOUS LINEAR	v
					0
					1
					1
					2
					5
					1
					2
					4
					6
					1
					2
Uv(2):Diet - Roots	(kg/y)	Yearly human consumption of other vegetables	Behavioral	CONTINUOUS LINEAR	v
					0
					2
					4
					5
					1
					2
					5
					7
					1
					3
					3
Uv(3):Diet - Fruit	(kg/y)	Yearly human consumption of fruits	Behavioral	CONTINUOUS LINEAR	v
					0
					1
					3
					5
					9
					2
					4
					1
					1
					4

					6
Uv(4):Diet - Grain	(kg/y)	Yearly human consumption of grains	Behavioral	CONTINUOUS LINEAR	V
					0
					1
					2
					3
					4
					8
					1
					3
					4
					8
					9
Ua(1):Diet - Beef	(kg/y)	Yearly human consumption of beef	Behavioral	CONTINUOUS LINEAR	V
					0
					2
					7
					8
					1
					2
					4
					7
					1
					2
					2
Ua(2):Diet - Poultry	(kg/y)	Yearly human consumption of poultry	Behavioral	CONTINUOUS LINEAR	V
					0
					3
					4
					5
					9
					1
					3
					5
					5
					7
					7
Ua(3):Diet - Milk	(L/y)	Yearly human consumption of milk	Behavioral	CONTINUOUS LINEAR	V
					0
					6
					6
					7
					5
					1
					2
					5
					7
					1
					1
Ua(4):Diet - Egg	(kg/y)	Yearly human consumption of eggs	Behavioral	CONTINUOUS LINEAR	V
					0
					2
					4
					5
					8
					1
					2
					3
					4
					1
					1
Uf:Diet - Fish	(kg/y)	Yearly human consumption of fish produced from an onsite pond	Behavioral	CONTINUOUS LINEAR	V
					0
					1
					1
					2
					3
					7
					1
					3
					7
					1
					8
UW:Diet - Water	(L/d)	Drinking water ingestion rate	Behavioral	LOGNORMAL-N	M
					S
tf:Consumption Period	(days)	Consumption period for fish	Behavioral	CONSTANT	V
tcv(1):Consumption Period - Leafy	(days)	Food consumption period for leafy vegetables	Behavioral	CONSTANT	V
tcv(2):Consumption Period - Roots	(days)	Food consumption period for other vegetables	Behavioral	CONSTANT	V
tcv(3):Consumption Period - Fruit	(days)	Food consumption period for fruits	Behavioral	CONSTANT	V

tcv(4):Consumption Period - Grain	(days)	Food consumption period for grains	Behavioral	CONSTANT	v
tca(1):Consumption Period - Beef	(days)	Food consumption period for beef	Behavioral	CONSTANT	v
tca(2):Consumption Period - Poultry	(days)	Food consumption period for poultry	Behavioral	CONSTANT	v
tca(3):Consumption Period - Milk	(days)	Food consumption period for milk	Behavioral	CONSTANT	v
tca(4):Consumption Period - Egg	(days)	Food consumption period for eggs	Behavioral	CONSTANT	v
THV(1):Holdup Period : Leafy	(days)	Holdup period for leafy vegetables	Behavioral	CONSTANT	v
THV(2):Holdup Period : Other vegetables	(days)	Holdup period for other vegetables	Behavioral	CONSTANT	v
THV(3):Holdup Period : Fruits	(days)	Holdup period for fruits	Behavioral	CONSTANT	v
THV(4):Holdup Period : Grains	(days)	Holdup period for grains	Behavioral	CONSTANT	v
THA(1):Holdup Period : Beef	(days)	Holdup period for beef	Behavioral	CONSTANT	v
THA(2):Holdup Period : Poultry	(days)	Holdup period for poultry	Behavioral	CONSTANT	v
THA(3):Holdup Period : Milk	(days)	Holdup period for milk	Behavioral	CONSTANT	v
THA(4):Holdup Period : Eggs	(days)	Holdup period for eggs	Behavioral	CONSTANT	v
TGV(1):Growing Period : Leafy	(days)	Minimum growing period for leafy vegetables	Physical	CONSTANT	v
TGV(2):Growing Period : Other vegetables	(days)	Minimum growing period for other vegetables	Physical	CONSTANT	v
TGV(3):Growing Period : Fruits	(days)	Minimum growing period for fruits	Physical	CONSTANT	v
TGV(4):Growing Period : Grains	(days)	Minimum growing period for grains	Physical	CONSTANT	v
TGF(1):Growing Period : Beef Forage	(days)	Minimum growing period for forage consumed by beef cattle	Physical	CONSTANT	v
TGF(2):Growing Period : Poultry Forage	(days)	Minimum growing period for forage consumed by poultry	Physical	DERIVED	
TGF(3):Growing Period : Milk Cow Forage	(days)	Minimum growing period for forage consumed by milk cows	Physical	DERIVED	
TGF(4):Growing Period : Layer Hen Forage	(days)	Minimum growing period for forage consumed by layer hens	Physical	DERIVED	
TGG(1):Growing Period : Beef Cow Grain	(days)	Minimum growing period for stored grain consumed by beef cattle	Physical	CONSTANT	v
TGG(2):Growing Period : Poultry Grain	(days)	Minimum growing period for stored grain consumed by poultry	Physical	DERIVED	
TGG(3):MGrowing Period : Milk Cow Grain	(days)	Minimum growing period for stored grain consumed by milk cows	Physical	DERIVED	
TGG(4):Growing Period : Layer Hen Grain	(days)	Minimum growing period for stored grain consumed by layer hens	Physical	DERIVED	
TGH(1):Growing Period : Beef Cow Hay	(days)	Minimum growing period for stored hay consumed by beef cattle	Physical	CONSTANT	v
TGH(2):Growing Period : Poultry Hay	(days)	Minimum growing period for stored hay consumed by poultry	Physical	DERIVED	
TGH(3):Growing Period : Milk Cow Hay	(days)	Minimum growing period for stored hay consumed by milk cows	Physical	DERIVED	
TGH(4):Growing Period : Layer Hen Hay	(days)	Minimum growing period for stored hay consumed by layer hens	Physical	DERIVED	
SATac:Animal Product Specific Activity	(none)	Spec activ equivalence of animal product and spec activ of animal feed, forage, and soil	Physical	CONSTANT	v
sh:Soil Moisture Content	(L/m**3)	Moisture content of soil	Physical	DERIVED	
TFF(1):Feeding Period : Beef Cow Forage	(days)	Feeding period for beef cattle forage	Physical	CONSTANT	v
TFF(2):Feeding Period : Poultry Forage	(days)	Feeding period for poultry forage	Physical	CONSTANT	v
TFF(3):Feeding Period : Milk Cow Forage	(days)	Feeding period for milk cow forage	Physical	CONSTANT	v
TFF(4):Feeding Period : Layer Hen Forage	(days)	Feeding period for layer hen forage	Physical	CONSTANT	v
TFG(1):Feeding Period : Beef Cattle Grain	(days)	Feeding period for beef cattle grain	Physical	CONSTANT	v
TFG(2):Feeding Period : Poultry Grain	(days)	Feeding period for poultry grain	Physical	CONSTANT	v
TFG(3):Feeding Period : Milk Cow Grain	(days)	Feeding period for milk cow grain	Physical	CONSTANT	v
TFG(4):Feeding Period : Layer Hen Grain	(days)	Feeding period for layer hen grain	Physical	CONSTANT	v
TFH(1):Feeding Period : Beef Cattle Hay	(days)	Feeding period for beef cattle hay	Physical	CONSTANT	v
TFH(2):Feeding Period : Poultry Hay	(days)	Feeding period for poultry hay	Physical	CONSTANT	v
TFH(3):Feeding Period : Milk Cow Hay	(days)	Feeding period for milk cow hay	Physical	CONSTANT	v
TFH(4):Feeding Period : Layer Hen Hay	(days)	Feeding period for layer hen hay	Physical	CONSTANT	v
TFW(1):Water Period : Beef Cattle	(days)	Water ingestion period for beef cattle	Physical	CONSTANT	v
TFW(2):Water Period : Poultry	(days)	Water ingestion period for poultry	Physical	CONSTANT	v
TFW(3):Water Period : Milk Cows	(days)	Water ingestion period for milk cows	Physical	CONSTANT	v
TFW(4):Water Period : Layer Hens	(days)	Water ingestion period for layer hens	Physical	CONSTANT	v
YA(1):Animal Product Yield : Beef Cattle	(kg/y)	Annual yield of beef per individual animal	Physical	CONSTANT	v
YA(2):Animal Product Yield : Poultry	(kg/y)	Annual yield of chicken per individual animal	Physical	CONSTANT	v
YA(3):Animal Product Yield : Milk Coes	(L/y)	Annual yield of milk per individual animal	Physical	CONSTANT	v
YA(4):Animal Product Yield : Layer Hens	(kg/y)	Annual yield of eggs per individual animal	Physical	CONSTANT	v
RV(1):Interception Fraction : Leafy	(none)	Interception fraction for leafy vegetables	Physical	UNIFORM	L
					L
RV(2):Interception Fraction : Other vegetables	(none)	Interception fraction for other vegetables	Physical	UNIFORM	L
					L
RV(3):Interception Fraction : Fruits	(none)	Interception fraction for fruits	Physical	UNIFORM	L
					L
RV(4):Interception Fraction : Grains	(none)	Interception fraction for grains	Physical	UNIFORM	L
					L
RF(1):Interception Fraction : Beef Forage	(none)	Interception fraction for beef cattle forage	Physical	UNIFORM	L
					L
RF(2):Interception Fraction : Poultry forage	(none)	Interception fraction for poultry forage	Physical	DERIVED	
RF(3):Interception Fraction : Milk Cow Forage	(none)	Interception fraction for milk cow forage	Physical	DERIVED	
RF(4):Interception Fraction : Layer Hen Forage	(none)	Interception fraction for layer hen forage	Physical	DERIVED	
RG(1):Interception Fraction : Beef Cow Grain	(none)	Interception fraction for beef cattle grain	Physical	UNIFORM	L
					L
RG(2):Interception Fraction : Poultry Grain	(none)	Interception fraction for poultry grain	Physical	DERIVED	
RG(3):Interception Fraction : Milk Cow Grain	(none)	Interception fraction for milk cow grain	Physical	DERIVED	
RG(4):Interception Fraction : Layer Hen Grain	(none)	Interception fraction for layer hen grain	Physical	DERIVED	
RH(1):Interception Fraction : Beef Cow Hay	(none)	Interception fraction for beef cattle hay	Physical	DERIVED	
RH(2):Interception Fraction : Poultry Hay	(none)	Interception fraction for poultry hay	Physical	DERIVED	
RH(3):Interception Fraction : Milk Cow Hay	(none)	Interception fraction for milk cow hay	Physical	DERIVED	
RH(4):Interception Fraction : Layer Hen Hay	(none)	Interception fraction for layer hen hay	Physical	DERIVED	
Tv(1):Translocation:Leafy	(none)	Translocation factor for leafy vegetables	Physical	CONSTANT	v

Tv(2):Translocation:Root	(none)	Translocation factor for other vegetables	Physical	CONSTANT	v
Tv(3):Translocation:Fruit	(none)	Translocation factor for fruit	Physical	CONSTANT	v
Tv(4):Translocation:Grain	(none)	Translocation factor for grain	Physical	CONSTANT	v
Tf(1):Translocation:Beef Forage	(none)	Translocation factor for forage consumed by beef cattle	Physical	CONSTANT	v
Tf(2):Translocation:Poultry Forage	(none)	Translocation factor for forage consumed by poultry	Physical	CONSTANT	v
Tf(3):Translocation:Translocation:	(none)	Translocatioin factor for forage consumed by milk cows	Physical	CONSTANT	v
Tf(4):Translocation:Layer Hen Forage	(none)	Translocation factor for forage consumed by layer hens	Physical	CONSTANT	v
Tg(1):Translocation:Beef Grain	(none)	Translocation factor for stored grain consumed by beef cattle	Physical	CONSTANT	v
Tg(2):Translocation:Poultry Grain	(none)	Translocation factor for stored grain consumed by poultry	Physical	CONSTANT	v
Tg(3):Translocation:Milk Cow Grain	(none)	Translocation factor for stored grain consumed by milk cows	Physical	CONSTANT	v
Tg(4):Translocation:Layer Hen Grain	(none)	Translocation factor for stored grain consumed by layer hens	Physical	CONSTANT	v
Th(1):Translocation:Beef Hay	(none)	Translocation factor for stored hay consumed by beef cattle	Physical	CONSTANT	v
Th(2):Translocation:Poultry Hay	(none)	Translocation factor for stored hay consumed by poultry	Physical	CONSTANT	v
Th(3):Translocation:Milk Cow Hay	(none)	Translocation factor for stored hay consumed by milk cows	Physical	CONSTANT	v
Th(4):Translocation:Layer Hen Hay	(none)	Translocation factor for stored hay consumed by layer hens	Physical	CONSTANT	v
xf(1):Beef Forage Contaminated Fraction	(none)	Fraction of forage consumed by beef cattle that is contaminated	Physical	CONSTANT	v
xf(2):Poultry Forage Contaminated Fraction	(none)	Fraction of forage consumed by poultry that is contaminated	Physical	CONSTANT	v
xf(3):Milk Cow Forage Contaminated Fraction	(none)	Fraction of forage consumed by milk cows that is contaminated	Physical	CONSTANT	v
xf(4):Layer Hen Forage Contaminated Fraction	(none)	Fraction of forage consumed by layer hens that is contaminated	Physical	CONSTANT	v
xg(1):Beef Grain Contaminated Fraction	(none)	Fraction of stored grain consumed by beef cattle that is contaminated	Physical	CONSTANT	v
xg(2):Poultry Grain Contaminated Fraction	(none)	Fraction of stored grain consumed by poultry that is contaminated	Physical	CONSTANT	v
xg(3):Milk Cow Grain Contaminated Fraction	(none)	Fraction of stored grain consumed by milk cows that is contaminated	Physical	CONSTANT	v
xg(4):Layer Hen Grain Contaminated Fraction	(none)	Fraction of stored grain that is consumed by layer hens that is contaminated	Physical	CONSTANT	v
xh(1):Beef Hay Contaminated Fraction	(none)	Fraction of stored hay consumed by beef cattle that is contaminated	Physical	CONSTANT	v
xh(2):Poultry Hay Contaminated Fraction	(none)	Fraction of stored hay consumed by poultry that is contaminated	Physical	CONSTANT	v
xh(3):Milk Cow Hay Contaminated Fraction	(none)	Fraction of stored hay consumed by milk cows that is contaminated	Physical	CONSTANT	v
xh(4):Layer Hen Hay Contaminated Fraction	(none)	Fraction of stored hay consumed by layer hens that is contaminated	Physical	CONSTANT	v
xw(1):Beef Water Contaminated Fraction	(none)	Fraction of water that is consumed by beef cattle that is contaminated	Physical	CONSTANT	v
xw(2):Poultry Water Contaminated Fraction	(none)	Fraction of water consumed by poultry that is contaminated	Physical	CONSTANT	v
xw(3):Milk Cow Water Contaminated Fraction	(none)	Fraction of water consumed by milk cows that is contaminated	Physical	CONSTANT	v
xw(4):Layer Hen Water Contaminated Fraction	(none)	Fraction of water consumed by layer hens that is contaminated	Physical	CONSTANT	v
YV(1):Crop Yield : Leafy	(kg wet wt/m**2)	Crop yield for leafy vegetables	Physical	CONTINUOUS LINEAR	v
					2
					2
					2
					2
					2
					2
					2
					2
					2
					2
					2
					2
					2
					2
					2
					3
					3
					3
					3
					3
					3
					3
YV(2):Crop Yeild : Other	(kg wet wt/m**2)	Crop yield for other vegetables	Physical	CONTINUOUS LINEAR	v
					2
					2
					2
					2
					2
					2
					2
					2
					2
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					2

					2
					2
YV(3):Crop Yield : Fruits	(kg wet wt/m**2)	Crop yield for fruits	Physical	CONTINUOUS LINEAR	V
					2
					2
					2
					2
					2
					2
					2
					2
					2
					2
					2
					2
					2
					2
					2
					2
					2
					2
					2
					2
YV(4):Crop Yield : Grains	(kg wet wt/m**2)	Crop yield for grains	Physical	CONTINUOUS LINEAR	V
					0
					0
					0
					0
					0
					0
					0
					0
					0
					0
					0
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					0
					0
					0
					0
YF(1):Crop Yield : Beef Forage	(kg dry wt forage/m**2)	Crop yield for beef cattle forage	Physical	BETA	L
					L
					p
					q
YF(2):Crop Yield : Poultry Forage	(kg wet wt forage/m**2)	Crop yield for poultry forage	Physical	DERIVED	
YF(3):Crop Yield : Milk Cow Forage	(kg wet wt forage/m**2)	Crop yield for milk cow forage	Physical	DERIVED	
YF(4):Crop Yield : Layer Hen Forage	(kg wet wt forage/m**2)	Crop yield for layer hen forage	Physical	DERIVED	
YG(1):Crop Yield : Beef Cow Grain	(kg dry wt grain /m**2)	Crop yield for beef cattle grain	Physical	NORMAL	M
					S
YG(2):Crop Yield : Poultry Grain	(kg wet wt grain /m**2)	Crop yield for poultry grain	Physical	DERIVED	
YG(3):Crop Yield : Milk Cow Grain	(kg wet wt grain /m**2)	Crop yield for milk cow grain	Physical	DERIVED	
YG(4):Crop Yield : Layer Hen Grain	(kg wet wt grain /m**2)	Crop yield for layer hen grain	Physical	DERIVED	
YH(1):Crop Yield : Beef Cow Hay	(kg wet wt/m**2)	Crop yield for beef cattle hay	Physical	DERIVED	
YH(2):Crop Yield : Poultry Hay	(kg wet wt/m**2)	Crop yield for poultry hay	Physical	DERIVED	
YH(3):Crop Yield : Milk Cow Hay	(kg wet wt/m**2)	Crop yield for milk cow hay	Physical	DERIVED	
YH(4):Crop Yield : Layer Hen Hay	(kg wet wt/m**2)	Crop yield for layer hen hay	Physical	DERIVED	
WV(1):Wet/dry : Leafy Vegetables	(none)	Wet/dry conversion factor for leafy vegetables	Physical	CONTINUOUS LINEAR	V
					0
					0
					0
					0
					0
					0
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					0
WV(2):Wet/dry : Other Vegetables	(none)	Wet/dry conversion factor for other vegetables	Physical	CONTINUOUS LINEAR	v
					0
					0
					0
					0
					0
					0
					0
					0
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WV(3):Wet/dry : Fruit	(none)	Wet/dry conversion factor for fruits	Physical	CONTINUOUS LINEAR	v
					0
					0
					0
					0
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					0
					0
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WV(4):Wet/dry : Grain	(none)	Wet/dry conversion factor for grains	Physical	CONSTANT	v
WF(1):Wet/dry : Beef Cow Forage	(none)	Wet/dry conversion factor for beef cattle forage	Physical	BETA	L
					L
					p
					q
WF(2):Wet/dry : Poultry Forage	(none)	Wet/dry conversion factor for poultry forage	Physical	DERIVED	
WF(3):Wet/dry : Milk Cow Forage	(none)	Wet/dry conversion factor for milk cow forage	Physical	DERIVED	
WF(4):Wet/dry : Layer Hen Forage	(none)	Wet/dry conversion factor for layer hen forage	Physical	DERIVED	
WG(1):Wet/dry : Beef Cow Grain	(none)	Wet/dry conversion factor for beef cattle grain	Physical	CONSTANT	v
WG(2):Wet/dry : Poultry Grain	(none)	Wet/dry conversion factor for poultry grain	Physical	DERIVED	
WG(3):Wet/dry : Milk Cow Grain	(none)	Wet/dry conversion factor for milk cow grain	Physical	DERIVED	
WG(4):Wet/dry : Layer Hen Grain	(none)	Wet/dry conversion factor for layer hen grain	Physical	DERIVED	
WH(1):Wet/dry : Beef Cow Hay	(none)	Wet/dry conversion factor for beef cattle hay	Physical	DERIVED	
WH(2):Wet/dry : Poultry Hay	(none)	Wet/dry conversion factor for poultry hay	Physical	DERIVED	
WH(3):Wet/dry : Milk Cow Hay	(none)	Wet/dry conversion factor for milk cow hay	Physical	DERIVED	
WH(4):Wet/dry : Layer Hen Hay	(none)	Wet/dry conversion factor for layer hen hay	Physical	DERIVED	
QF(1):Ingestion Rate : Beef Cow Forage	(kg dry wt forage/d)	Ingestion rate for beef cattle forage	Physical	BETA	L
					L
					p
					q
QF(2):Ingestion Rate : Poultry Forage	(kg dry wt forage/d)	Ingestion rate for poultry forage	Physical	BETA	L
					L
					p
					q
QF(3):Ingestion Rate : Milk Cow Forage	(kg dry wt forage/d)	Ingestion rate for milk cow forage	Physical	CONTINUOUS LINEAR	v
					6
					6
					6
					7
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					1
					1
QF(4):Ingestion Rate : Layer Hen Forage	(kg dry wt forage/d)	Ingestion rate for layer hen forage	Physical	BETA	L
					L
					p
					q
QG(1):Ingestion Rate : Beef Cattle Grain	(kg dry wt grain/d)	Ingestion rate for beef cattle grain	Physical	BETA	L
					L
					p
					q
QG(2):Ingestion Rate : Poultry Grain	(kg dry wt grain/d)	Ingestion rate for poultry grain	Physical	BETA	L

					L
					p
					q
QG(3):Ingestion Rate : Milk Cow Grain	(kg dry wt grain/d)	Ingestion rate for milk cow grain	Physical	NORMAL	M
					S
QG(4):Ingestion Rate : Layer Hen Grain	(kg dry wt grain/d)	Ingestion rate for layer hen grain	Physical	BETA	L
					L
					p
					q
QH(1):Ingestion Rate : Beef Cattle Hay	(kg wet wt hay/d)	Ingestion rate for beef cattle hay	Physical	BETA	L
					L
					p
					q
QH(2):Ingestion Rate : Poultry Hay	(kg dry wt hay/d)	Ingestion rate for poultry hay	Physical	CONSTANT	V
QH(3):Ingestion Rate : Milk Cow Hay	(kg wet wt hay/d)	Ingestion rate for milk cow hay	Physical	CONTINUOUS LINEAR	V
					5
					5
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					9
					1
					1
QH(4):Ingestion Rate : Layer Hen Hay	(kg dry wt hay/d)	Ingestion rate for layer hen hay	Physical	CONSTANT	V
QW(1):Water Rate : Beef Cattle	(L/d)	Water ingestion rate for beef cattle	Physical	CONSTANT	V
QW(2):Water Rate : Poultry	(L/d)	Water ingestion rate for poultry	Physical	CONSTANT	V
QW(3):Water Rate : Milk Cows	(L/d)	Water ingestion rate for milk cows	Physical	CONSTANT	V
QW(4):Water Rate : Layer Hens	(L/d)	Water ingestion rate for layer hens	Physical	CONSTANT	V
QD(1):Soil Fraction : Beef Cattle	(none)	Soil intake fraction for beef cattle	Physical	CONSTANT	V
QD(2):Soil Fraction : Poultry	(none)	Soil intake fraction for poultry	Physical	CONSTANT	V
QD(3):Soil Fraction : Milk Cows	(none)	Soil intake fraction for milk cows	Physical	CONSTANT	V
QD(4):Soil Fraction : Layer Hens	(none)	Soil intake fraction for layer hens	Physical	CONSTANT	V
MLV(1):Mass-Loading : Leafy Vegetables	(none)	Mass-loading factor for leafy vegetables	Physical	CONSTANT	V
MLV(2):Mass-Loading : Other Vegetables	(none)	Mass-loading factor for other vegetables	Physical	CONSTANT	V
MLV(3):Mass-Loading : Fruits	(none)	Mass-loading factor for fruits	Physical	CONSTANT	V
MLV(4):Mass-Loading : Grains	(none)	Mass-loading factor for grains	Physical	CONSTANT	V
LAMBDW:Weathering Rate	(1/d)	Weathering rate for activity removal from plants	Physical	CONSTANT	V
MLF(1):Mass-Loading : Beef Cow Forage	(none)	Mass-loading factor for beef cattle forage	Physical	CONSTANT	V
MLF(2):Mass-Loading : Poultry Forage	(none)	Mass-loading factor for poultry forage	Physical	CONSTANT	V
MLF(3):Mass-Loading : Milk Cow Forage	(none)	Mass-loading factor for milk cow forage	Physical	CONSTANT	V
MLF(4):Mass-Loading : Layer Hen Forage	(none)	Mass-loading factor for layer hen forage	Physical	CONSTANT	V
MLG(1):Mass-Loading : Beef Cattle Grain	(none)	Mass-loading factor for beef cattle grain	Physical	CONSTANT	V
MLG(2):Mass-Loading : Poultry Grain	(none)	Mass-loading factor for poultry grain	Physical	CONSTANT	V
MLG(3):Mass-Loading : Milk Cow Grain	(none)	Mass-loading factor for milk cow grain	Physical	CONSTANT	V
MLG(4):Mass-Loading : Layer Hen Grain	(none)	Mass-loading factor for layer hen grain	Physical	CONSTANT	V
MLH(1):Mass-Loading : Beef Cattle Hay	(none)	Mass-loading factor for beef cattle hay	Physical	CONSTANT	V
MLH(2):Mass-Loading : Poultry Hay	(none)	Mass-loading factor for poultry hay	Physical	CONSTANT	V
MLH(3):Mass-Loading : Milk Cow Hay	(none)	Mass-loading factor for milk cow hay	Physical	CONSTANT	V
MLH(4):Mass-Loading : Layer Hen Hay	(none)	Mass-loading factor for layer hen hay	Physical	CONSTANT	V
fca(1):Beef Carbon Fraction	(none)	Mass fraction of beef cattle that is carbon	Physical	CONSTANT	V
fca(2):Poultry Carbon Fraction	(none)	Mass fraction of poultry that is carbon	Physical	CONSTANT	V
fca(3):Milk Carbon Fraction	(none)	Mass fraction of milk that is carbon	Physical	CONSTANT	V
fca(4):Eggs Carbon Fraction	(none)	Mass fraction of an egg that is carbon	Physical	CONSTANT	V

fcf(1):Beef Forage Carbon Fraction	(none)	Mass fraction of wet forage consumed by beef cattle that is carbon	Physical	CONSTANT	v
fcf(2):Poultry Forage Carbon Fraction	(none)	Mass fraction of wet forage consumed by poultry that is carbon	Physical	CONSTANT	v
fcf(3):Milk Cow Forage Carbon Fraction	(none)	Mass fraction of wet forage consumed by milk cows that is carbon	Physical	CONSTANT	v
fcf(4):Layer Hen Forage Carbon Fraction	(none)	Mass fraction of wet forage consumed by layer hens that is carbon	Physical	CONSTANT	v
fcg(1):Beef Grain Carbon Fraction	(none)	Mass fraction of wet stored grain consumed by beef cattle that is carbon	Physical	CONSTANT	v
fcg(2):Poultry Grain Carbon Fraction	(none)	Mass fraction of wet stored grain consumed by poultry that is carbon	Physical	CONSTANT	v
fcg(3):Milk Cow Grain Carbon Fraction	(none)	Mass fraction of wet stored grain consumed by milk cows that is carbon	Physical	CONSTANT	v
fcg(4):Layer Hen Grain Carbon Fraction	(none)	Mass fraction of wet stored grain consumed by layer hens that is carbon	Physical	CONSTANT	v
fch(1):Beef Hay Carbon Fraction	(none)	Mass fraction of wet stored hay consumed by beef cattle that is carbon	Physical	CONSTANT	v
fch(2):Poultry Hay Carbon Fraction	(none)	Mass fraction of wet stored hay consumed by poultry that is carbon	Physical	CONSTANT	v
fch(3):Milk Cow Hay Carbon Fraction	(none)	Mass fraction of wet stored hay consumed by milk cows that is carbon	Physical	CONSTANT	v
fch(4):Layer Hen Hay Carbon Fraction	(none)	Mass fraction of wet stored hay consumed by layer hens that is carbon	Physical	CONSTANT	v
fCd:Soil Carbon Fraction	(none)	Mass fraction of dry soil that is carbon	Physical	CONSTANT	v
fha(1):Hydrogen Fraction : Beef Cattle	(none)	Hydrogen fraction for beef cattle	Physical	CONSTANT	v
fha(2):Hydrogen Fraction : Poultry	(none)	Hydrogen fraction for poultry	Physical	CONSTANT	v
fha(3):Hydrogen Fraction : Milk Cows	(none)	Hydrogen fraction for milk cows	Physical	CONSTANT	v
fha(4):Hydrogen Fraction : Layer Hens	(none)	Hydrogen fraction for layer hens	Physical	CONSTANT	v
fhv(1):Hydrogen Fraction : Leafy Vegetables	(none)	Hydrogen fraction for leafy vegetables	Physical	CONSTANT	v
fhv(2):Hydrogen Fraction : Other Vegetables	(none)	Hydrogen fraction for other vegetables	Physical	CONSTANT	v
fhv(3):Hydrogen Fraction : Fruits	(none)	Hydrogen fraction for fruits	Physical	CONSTANT	v
fhv(4):Hydrogen Fraction : Grains	(none)	Hydrogen fraction for grains	Physical	CONSTANT	v
fhf(1):Hydrogen Fraction : Beef Cow Forage	(none)	Hydrogen fraction for beef cattle forage	Physical	CONSTANT	v
fhf(2):Hydrogen Fraction : Poultry Forage	(none)	Hydrogen fraction for poultry forage	Physical	CONSTANT	v
fhf(3):Hydrogen Fraction : Milk Cow Forage	(none)	Hydrogen fraction for milk cow forage	Physical	CONSTANT	v
fhf(4):Hydrogen Fraction : Layer Hen Forage	(none)	Hydrogen fraction for layer hen forage	Physical	CONSTANT	v
fhh(1):Hydrogen Fraction : Beef Cattle Hay	(none)	Hydrogen fraction for beef cattle hay	Physical	CONSTANT	v
fhh(2):Hydrogen Fraction : Poultry Hay	(none)	Hydrogen fraction for poultry hay	Physical	CONSTANT	v
fhh(3):Hydrogen Fraction : Milk Cow Hay	(none)	Hydrogen fraction for milk cow hay	Physical	CONSTANT	v
fhh(4):Hydrogen Fraction : Layer Hen Hay	(none)	Hydrogen fraction for layer hen hay	Physical	CONSTANT	v
fhg(1):Hydrogen Fraction : Beef Cattle Grain	(none)	Hydrogen fraction for beef cattle grain	Physical	CONSTANT	v
fhg(2):Hydrogen Fraction : Poultry Grain	(none)	Hydrogen fraction for poultry grain	Physical	CONSTANT	v
fhg(3):Hydrogen Fraction : Milk Cow Grain	(none)	Hydrogen fraction for milk cow grain	Physical	CONSTANT	v
fhg(4):Hydrogen Fraction : Layer Hen Grain	(none)	Hydrogen fraction for layer hen grain	Physical	CONSTANT	v
fhd016:Hydrogen Fraction : Soil	(none)	Fraction of hydrogen in soil	Physical	DERIVED	
sasvh:Tritium Equivalence: Plant/Soil	(none)	Tritium equivalence: plant/soil	Physical	CONSTANT	v
sawvh:Tritium Equivalence: Plant/Water	(none)	Tritium equivalence: plant/water	Physical	CONSTANT	v
satah:Tritium Equivalence: Animal Products	(none)	Tritium equivalence: animal product intake	Physical	CONSTANT	v

Table C7.4 Assigned Distribution Types and Distribution's Statistical Parameters for RESRAD-BUILI

Parameter	Classification	Assigned Distribution Type	Distribution's Statistica		
			1	2	
Removable fraction	Physical, Behavioral	Triangular	0	1	
Resuspension rate (1/s)	Physical, Behavioral	Loguniform	0	0.00001	
Shielding density (g/cm^3)	Physical	Uniform	2.2	2.6	
Source density, volume source (g/cm^3)	Physical	Uniform	2.2	2.6	
Air exchange rate for building and room (1/h)	Behavioral	Lognormal-n (truncated)	0.4187	0.88	
Air release fraction	Behavioral	Triangular	0.000001	1	
Deposition velocity (m/s)	Physical	Loguniform	0.000003	0.0027	
Direct ingestion rate (g/h for volume source and 1/h for all other sources)	Behavioral	None recommended			
Humidity (g/m^3)	Physical, Behavioral	Uniform	6.5	13.1	
Indoor fraction	Behavioral	Empirical	Defined by cumulative probability (Tat		
Receptor indirect ingestion rate (m^2/h)	Behavioral	Loguniform	0.000028	0.00029	
Receptor inhalation rate (m^3/d)	Metabolic, Behavioral	Triangular	12	46	
Room area (m^2)	Physical	Triangular	3	900	
Room height (m)	Physical	Triangular	2.4	9.1	
Shielding thickness (cm)	Physical, Behavioral	Triangular	0	30	
Source erosion rate, volume source (cm/d)	Physical, Behavioral	Triangular	0	0	
Source porosity	Physical	Uniform	0.04	0.25	
Source thickness, volume source (cm)	Physical	Triangular	2.5	30	
Time for source removal or source lifetime (d)	Physical, Behavioral	Triangular	1000	100000	
Volumetric water content	Physical	Uniform	0.04	0.25	
Water fraction available for evaporation	Physical	Triangular	0.5	1	
Wet + dry zone thickness (cm)	Physical	Uniform	5	30	

Table C7.5 Distribution types for RESRAD-BUILD and RESRAD

Distribution	Input Variables			
Beta	A (minimum)	B (maximum)	p (shape factor)	q (shape factor)
Exponential Types				
Exponential	?			
Bounded exponential	?	A (minimum)	B (maximum)	
Truncated exponential	?	lower quantile value	upper quantile value	
Gamma	*a* (shape factor)	ß (scale factor)		
Inverse Gaussian	μ	?		
Lognormal Types				
Lognormal	μ (mean)	error factor		
Lognormal-b	value at 0.001 quantile	value at 0.999 quantile		
Lognormal-n	mean of underlying normal distribution	standard dev. of underlying normal distribution		
Bounded lognormal	μ (mean)	error factor	A (minimum)	B (maximum)
Bounded lognormal-n	mean of underlying normal distribution	standard dev. of underlying normal distribution	A (minimum)	B (maximum)
Truncated lognormal	μ (mean)	error factor	lower quantile value	upper quantile value
Truncated lognormal-n	mean of underlying normal distribution	standard dev. of underlying normal distribution	lower quantile value	upper quantile value
Loguniform Types				
Loguniform	A (minimum)	B (maximum)		
Piecewise loguniform	number of intervals	# observations per interval 1…	# observations per interval n	first point, end point sequence
Maximum Entropy	A (minimum)	B (maximum)	μ (mean)	
Normal Types				
Normal	μ (mean)	*s* (standard deviation)		
Normal-b	value at 0.001 quantile	value at 0.999 quantile		
Bounded normal	μ (mean)	*s* (standard deviation)	A (minimum)	B (maximum)
Truncated normal	μ (mean)	*s* (standard deviation)	lower quantile value	upper quantile value
Pareto	*a*	ß		
Triangular	a (minimum)	b (most likely)	c (maximum)	
Uniform Types				
Uniform	A (minimum)	B (maximum)		
Piecewise uniform	number of intervals	# observations per interval 1…	# observations per interval n	first point, end point sequence
User Defined Types				
With linear interpolation (CDF input)	n (number of ordered pairs)	ordered pair 1	ordered pair 2 …	ordered pair n
With logarithmic interpolation (CDF input)	n (number of ordered pairs)	ordered pair 1	ordered pair 2 …	ordered pair n
With density function input	n (number of ordered pairs)	ordered pair 1	ordered pair 2 …	ordered pair n
Weibull	a	ß		

Table C7.6 Assigned Distribution Types and Distribution's Statistical Parameters for RESRAD Para

Parameter	Classification	Assigned Distribution Type	Distribution's Statistica		
			1	2	
Density of contaminated zone (g/cm^3)	Physical	Normal (truncated)	1.52	0.23	
Density of cover material (g/cm^3)	Physical	Normal (truncated)	1.52	0.23	
Density of saturated zone (g/m^3)	Physical	Normal (truncated)	1.52	0.23	
Depth of roots (m)	Physical	Uniform	0.3	4	
Distribution coefficients (contaminated zone, unsaturated zones, and saturated zone) (cm^3/g)	Physical	Lognormal-n (truncated)	Radionuclide specific (Table 3.9		
Saturated zone effective porosity	Physical	Normal (truncated)	0.355	0.0906	
Saturated zone hydraulic conductivity (m/yr)	Physical	Lognormal-n (bounded)	2.3	2.11	
Saturated zone total porosity	Physical	Normal (truncated)	0.425	0.0867	
Transfer factors for plants	Physical	Lognormal-n (truncated)	Element specific (Table 6.2-1		
Unsaturated zone thickness (m)	Physical	Lognormal-n (bounded)	2.296	1.276	
Aquatic food contaminated fraction	Behavioral, Physical	Triangular	0	1	
Bioaccumulation factors for fish [(pCi/kg)/(pCi/L)]	Physical	Lognormal-n	Element specific (Table 6.8-1		
C-14 evasion layer thickness in soil (m)	Physical	Triangular	0.2	0.6	
Contaminated zone b parameter	Physical	Lognormal-n (bounded)	1.06	0.66	
Inhalation rate (m^3/yr)	Metabolic, Physical	Triangular	4380	13100	
Contaminated zone erosion rate (m/yr)	Physical, Behavioral	Empirical	Defined by cumulative probability (Tat		
Contaminated zone hydraulic conductivity (m/yr)	Physical	Lognormal-n (bounded)	2.3	2.11	
Contaminated zone total porosity	Physical	Normal (truncated)	0.425	0.0867	
Cover depth (m)	Physical	None recommended			
Cover erosion rate (m/yr)	Physical, Behavioral	Empirical	Defined by cumulative probability (Tat		
Depth of soil mixing layer (m)	Physical	Triangular	0	0.6	
Drinking water intake (L/yr)	Metabolic, Behavioral	Lognormal-n (truncated)	6.015	0.489	
Evapotranspiration coefficient	Physical	Uniform	0.5	0.75	
External gamma shielding factor	Physical	Lognormal-n (bounded)	-1.3	0.59	
Fruit, vegetables, and grain consumption (kg/yr)	Metabolic, Behavioral	Triangular	135	318	
Indoor dust filtration factor	Physical, Behavioral	Uniform	0.15	0.95	
Mass loading for inhalation (µg/m^3)	Physical, Behavioral	Empirical	Defined by cumulative probability (Tat		
Milk consumption (L/yr)	Metabolic, Behavioral	Triangular	60	200	
Precipitation rate (m/yr)	Physical	Empirical	Defined by cumulative probability (Tat		
Runoff coefficient	Physical	Uniform	0.1	0.8	
Saturated zone b parameter	Physical	Lognormal-n (bounded)	1.06	0.66	
Saturated zone hydraulic gradient	Physical	Lognormal-n (bounded)	-5.11	1.77	
Soil ingestion rate (g/yr)	Metabolic, Behavioral	Triangular	0	36.5	
Transfer factors for meat [(pCi/kg)/(pCi/d)]	Physical	Lognormal-n (truncated)	Element specific (Table 6.3-1		
Transfer factors for milk [(pCi/L)/(pCi/d)]	Physical	Lognormal-n (truncated)	Element specific (Table 6.4-1		
Unsaturated zone density (g/cm^3)	Physical	Normal (truncated)	1.52	0.23	
Unsaturated zone effective porosity	Physical	Normal (truncated)	0.355	0.0906	
Unsaturated zone hydraulic conductivity (m/yr)	Physical	Lognormal-n (bounded)	2.3	2.11	
Unsaturated zone, soil-b parameter	Physical	Lognormal-n (bounded)	1.06	0.66	
Unsaturated zone total porosity	Physical	Normal (truncated)	0.425	0.0867	

Weathering removal constant (1/yr)	Physical	Triangular	5.1	84	
Well pumping rate (m^3/yr)	Behavioral, Physical	None recommended			
Well pump intake depth (below water table) (m)	Physical	Triangular	6	30	
Wet foliar interception fraction for leafy vegetables	Physical	Triangular	0.06	0.95	
Wet-weight crop yields for non-leafy vegetables (kg/m^2)	Physical	Lognormal-n (truncated)	0.56	0.48	
Wind speed (m/s)	Physical	Lognormal-n (bounded)	1.445	0.2419	
Humidity	Physical	Lognormal-n (truncated)	1.98	0.334	
Indoor fraction	Behavioral	Empirical	Defined by cumulative probability (Tat		

8.0 Criteria for Treating Uncertainty

8.1 Introduction

Uncertainty is inherent in all dose assessment calculations and must be considered in regulatory decision-making. In general, there are three primary sources of uncertainty in a dose assessment; uncertainty in the models, uncertainty in scenarios, and uncertainty in the parameters (Bonano et al., 1988, and Kozak et al., 1991). As stated in Section 5.0 (Criteria to Establish Conceptual Models), models are simplifications of reality, and in general, several alternative models may be consistent with available data. Uncertainty in scenarios is the result of our lack of knowledge about the future of the site. Parameter uncertainty results from incomplete knowledge of the model coefficients.

The NRC's risk-informed approach to regulatory decision-making suggests that an assessment of uncertainty be included in estimating doses. Specifically, the Probabilistic Risk Assessment (PRA) Policy Statement (60 FR 42622, August 16, 1995) states, in part, "The use of PRA technology should be increased in all regulatory matters to the extent supported by the state of the art in PRA methods and data, and in a manner that complements the NRC's deterministic approach . . . " In the past, dose assessments in support of NRC decommissioning requirements have primarily included the use of deterministic analyses. The deterministic approach has the advantage of being simple to implement and easy to communicate to a nonspecialist audience. However, it has a significant drawback in not allowing consideration of the effects of unusual combinations of input parameters and by not providing information on uncertainty in the results, which would be helpful to the decision-maker. Furthermore, a deterministic analysis that had a high assurance of not being exceeded would have to rely on the use of pessimistic estimates of each parameter of the model, often leading to overly conservative evaluations. Even with the use of probabilistic analyses, it is generally recognized that not all sources of uncertainty can be considered in a dose assessment, nor need to be considered. The primary emphasis in uncertainty analysis should be to identify the important assumptions and parameter values that, when altered, could change the decision.

Sensitivity analysis performed in conjunction with the uncertainty analysis can be used to identify parameters and assumptions that have the largest effect on the result. Sensitivity analysis provides a tool for understanding and explaining the influence of these key assumptions and parameter values on the variability of the estimated dose.

8.2 Issues in Uncertainty and Sensitivity Analyses

Uncertainty analysis imparts more information to the decision maker than deterministic analysis. It characterizes a range of potential doses and the likelihood that a particular dose would be exceeded.

An important issue in uncertainty and sensitivity analysis is that not all sources of uncertainty can be easily quantified. Of the three primary sources of uncertainty in dose assessment analyses, parameter uncertainty analysis is most mature. However, approaches for quantifying conceptual model and scenario uncertainty are less well-developed. Difficulties in predicting the

characteristics of future society, especially those influencing exposure, can lead to large uncertainties. At most, one is able to assert that an acceptably complete suite of scenarios has been considered in the assessment (Flavelle, 1992). For these reasons, we make no attempt to quantify formally model or scenario uncertainty, although to a certain extent, these are captured in parameter uncertainty analyses. Choices of the conceptual model(s) and scenarios to be used for the site are discussed in Sections 4 and 5.

Uncertainty analyses frequently use the Monte Carlo method. Input variables for the models are selected randomly from probability distribution functions (pdf's), which may be either independent or correlated to other input variable distributions. Critics of formal uncertainty analysis have often pointed out that limitations of knowledge about the nature and extent of correlation among variables fundamentally limit our ability to make meaningful statements about the degree of uncertainty in dose assessments (Smith et al., 1992).

Because the results of an uncertainty analysis provides a distribution of doses, it must be recognized that some percentage of the calculated doses may exceed the regulatory limit. A key issue that must be addressed in the treatment of uncertainty is specifying how to interpret the results from an uncertainty analysis in the context of a deterministic regulatory limit. Agency practice has not been to require absolute assurance that the regulatory limit will be met, so regulatory compliance could be stated in terms of a metric of the distribution such as the mean, or a percentage of calculated doses allowed to exceed the limit. Even for a deterministic analysis, it is recognized that the reported dose is simply one of a range of possible doses that could be calculated for the site; therefore, there is still an issue of where this calculated dose should lay in terms of the unquantified spectrum of possible doses.

In summary, the key issues in addressing uncertainty are: 1) incorporating alternative conceptual models and scenarios to identify a complete suite of possibilities, 2) determining how to select appropriate parameter distribution and ranges, along with the associated correlation between parameters for the analysis, and 3) specifying the metric of the dose distribution to use in determining compliance with the dose limit.

8.3 Recommended Approach

8.3.1 Screening Analyses

Often the first step in evaluating site compliance will be a "screening analysis". At preliminary stages of the evaluation, there may be little information available about the site. Therefore, the NRC screening approach is designed to ensure that there is high confidence that the dose will not be underestimated. As discussed in Sections 4 and 5 (Criteria for Modifying Pathways and Criteria to Establish Conceptual Models), the models and scenarios used in screening were selected to represent generic conditions and are intended to be "prudently conservative." The screening analysis assumes that all that is known about a site is the source term. Accordingly, the default parameters were selected to make it unlikely for the screening dose to exceed the dose that would be calculated using site-specific information.

NRC published a screening table for building-surface contamination (63 FR 64132). The staff performed a Monte Carlo analysis using the DandD code with values of the input parameters sampled from wide ranges selected to represent the variability in those parameters across the United States. The default values of input parameters for the DandD code, i.e., the values that the code would use without specification by the user, were then chosen from distributions of those parameters which would never cause the 90th percentile of the output dose distribution from the Monte Carlo analysis to be exceeded for any radionuclide, as illustrated in Figure C8.1 (Beyeler et al., 1999). Since DandD version 1.0 is a deterministic computer code, it is not necessary for the user to perform a Monte Carlo analysis for screening. The intent of the specification of default parameter values, scenario and conceptual models in the DandD code was to ensure that there will be less than a 10 percent probability that the calculated dose using site-specific information will exceed the dose limit. Because the default parameters, scenarios, and conceptual models in DandD version 1.0 are designed to provide high confidence that the dose will not be underestimated, an analyst using the code does not need to quantify the uncertainty in the dose analysis. The calculated results will be considered to represent a "prudently conservative" estimate of the dose (i.e., the calculated dose is likely an overestimation of the true dose). In many cases, however, the default parameter values chosen were highly conservative, making the outcome of the deterministic analysis overly stringent.

DandD version 2.0 is designed to allow Monte Carlo analyses which give a distribution of doses as illustrated in Figure C8.2. To maintain consistency in approaches used for versions 1 and 2, and

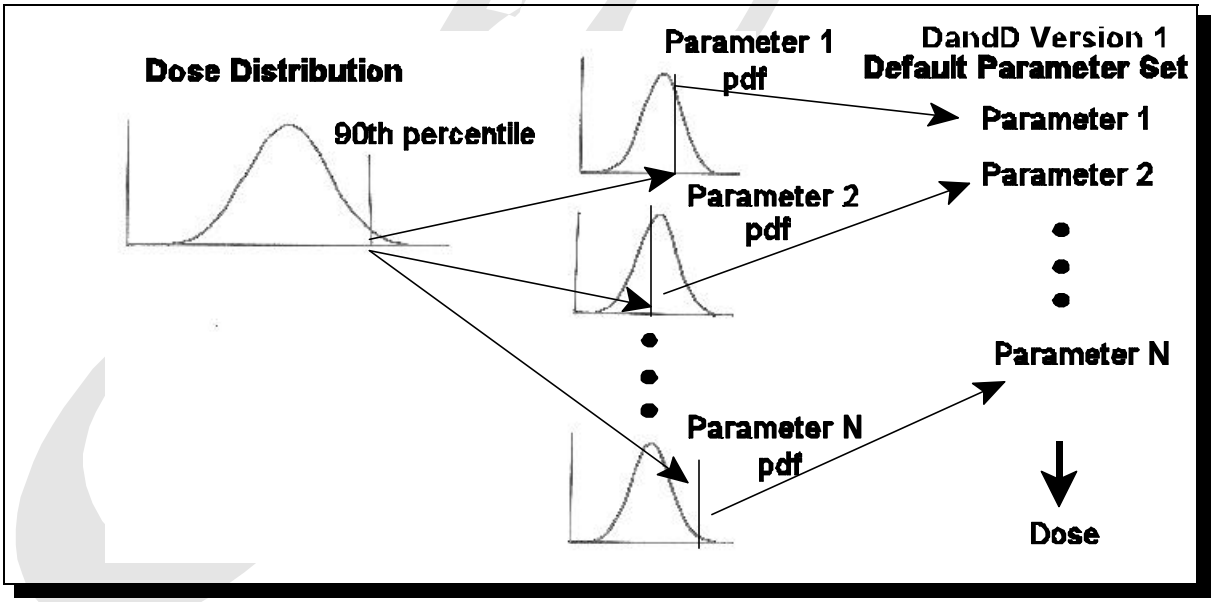

Figure C8.1 Treatment of parameter uncertainty in DandD Version 1.

previously published screening tables, the 90th percentile of the dose distribution should be used to determine compliance with the license termination rule when used for screening analysis. Default parameter probability density functions (pdf's) have been incorporated into the code for screening analyses; therefore, for screening analyses, the license reviewer will only need to ensure that these default pdf's were used.

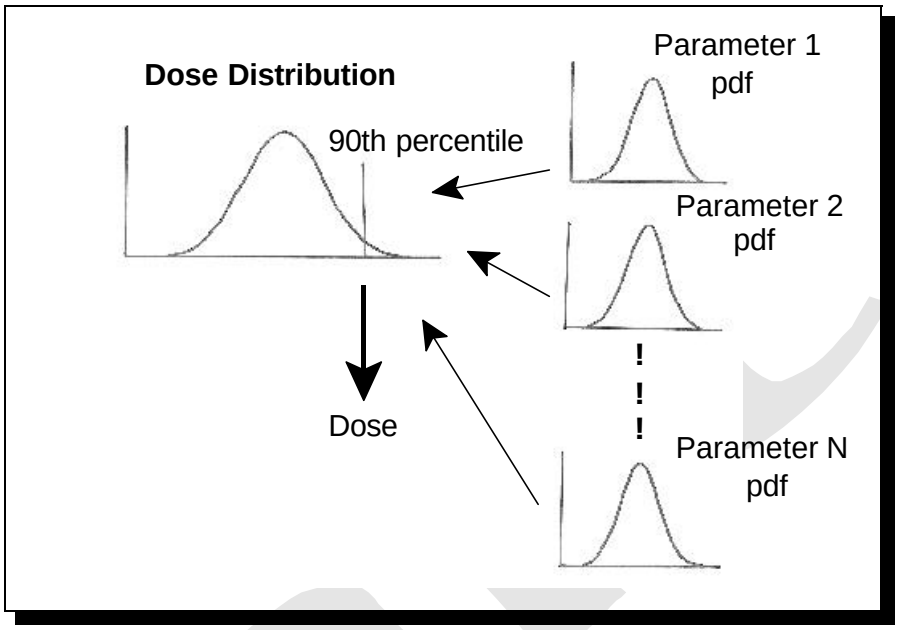

Figure C8.2 Treatment of parameter uncertainty in DandD Version 2.

8.3.2 Site-specific Analyses

8.3.2.1 Deterministic analysis

For site-specific analyses, the treatment of uncertainty in deterministic and probabilistic analyses should be handled differently. The NRC's risk-informed approach to regulatory decision-making suggests that an assessment of uncertainty should be included in dose analyses. However, in some cases such analyses may not be needed, e.g. bounding type analyses. Because no information is provided on the uncertainty in bounding analyses, it is important for the analyst to demonstrate that the single reported estimate of the peak dose is likely to be an overestimation of the actual peak dose. Use of conservatism in only some aspects of the analysis may not necessarily result in a conservative estimate of the dose. Uncertainties in the conceptual model may be larger than uncertainties in parameters used in the analysis; therefore, use of conservative parameter values do not necessarily ensure a conservative estimate of the dose. To ensure that the results from a deterministic analysis are unlikely to underestimate the dose, it is recommended that the analyst use the approaches discussed in Sections 4 and 5 (Criteria for Modifying Pathways and Criteria to Establish Conceptual Models) for developing land-use scenarios and

conceptual models. In addition, the analyst should use conservative values for key parameters. The approaches discussed below in Section 8.5, on performing sensitivity analyses should be used in identifying key parameters in the analysis.

8.3.2.2 Probabilistic analysis

While bounding analyses are a good starting point for determining regulatory compliance, the demonstration that a single, deterministic result is bounding may be too difficult to prove. For site-specific probabilistic analysis, it is only necessary to demonstrate that the mean dose does not exceed the regulatory criterion. A single deterministic calculation using the mean values of parameters is unlikely to result in the mean dose.

Parameter uncertainty analysis provides a quantitative method for estimating the uncertainty in calculated doses, assuming the structure of the model is an adequate representation of the real world and the exposure scenario is an appropriate reflection of potential future land-use at the site. Several methods have been developed for quantifying parameter uncertainty, including: 1) analytical methods, 2) Monte Carlo methods, 3) response surface methods, and 4) differential methods (Maheras and Kotecki, 1990). In addition, alternative approaches such as first-order reliability method, have recently been applied on a wide variety of environmental problems (Mirshra, 1998). Of these methods, the Monte Carlo methods are recommended because they are easy to implement and provide significant versatility.

Monte Carlo methods can be applied to either linear or nonlinear models, and analytical or numerical models. Input parameter uncertainties are represented as probability density functions. Parameter values randomly sampled from pdf's are used as inputs to multiple runs or "realizations" of the model.

For probabilistic analyses, the peak of the plot of mean dose over time should be compared to the regulatory standard to determine compliance. Equation 8.1 shows how the mean dose as a function of time can be derived.

Essentially, a mean dose is determined at each discrete time in the analysis. A plot is then made of these means over time. The mean dose provides the "best estimate" of dose at each discrete time. The overall peak of these best estimates is then used to determine compliance with the rule. Figure C8.3 shows how such a plot would be used to determine compliance with the regulations.

If the stated regulatory limits are exceeded, additional consideration should be given to allowing the proposed decommissioning action. The release-with-restrictions criteria assume that the land-use restrictions fail at some point. In some cases, especially with the use of durable institutional controls, it should be recognized that this will in general have a small likelihood of occurrence.

8.4 Input parameter distributions for Monte Carlo analysis

A key aspect of any Monte Carlo analysis is defining the ranges and statistical distribution of parameters treated as uncertain in the analysis. It is important for the analyst to avoid assigning overly restrictive ranges that suggest an unwarranted precision in the state of knowledge. On the other hand, specification of unreasonably large ranges may not account for what is known about a parameter and also lead to the result of "dose dilution". The distributions used in the analysis should characterize the degree of belief that the true but unknown value of a parameter lie within a specified range of values for that parameter.

Sensitivity results are generally less dependent on the actual distributions assigned to the input parameters than they are on the ranges chosen for the parameters. However, distributional

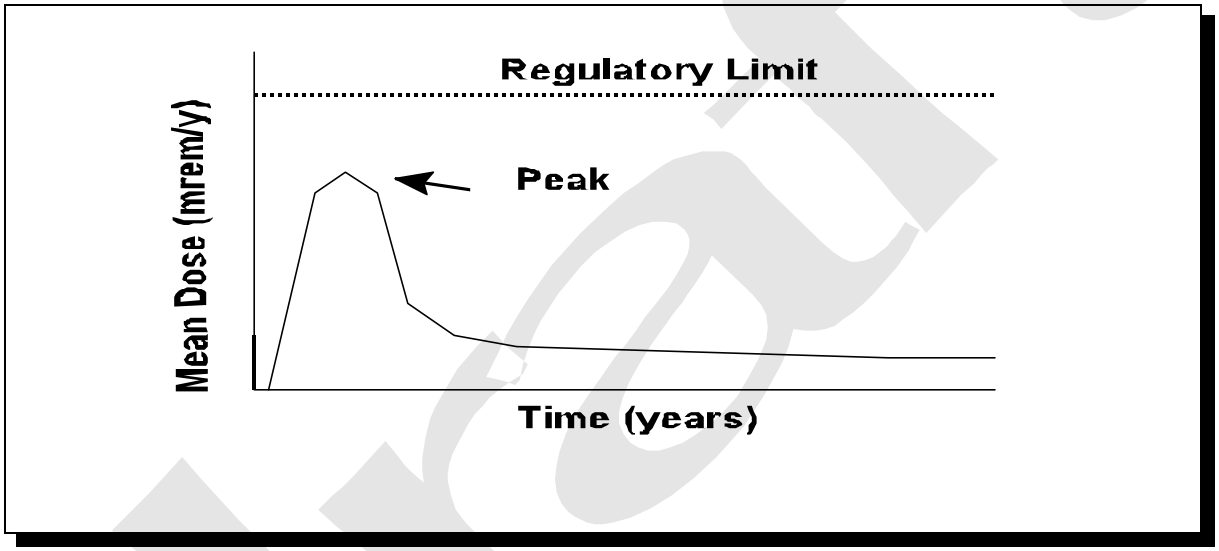

Figure C8.3 Application of Peak of the Mean Dose.

assumptions can have a large impact on the dose distribution (Helton, 1993). Resources can often be used most effectively by performing a Monte Carlo analysis in an iterative manner. Initially, rather crude ranges and distribution assumptions can be used to determine which input variables dominate the behavior of the calculated dose. Often, most of the variation in the calculated dose is caused by a relatively small subset of input parameters. Once the most important input parameters are identified, resources can be concentrated on characterizing their uncertainty. This avoids spending a large effort characterizing the uncertainty in parameters that have little impact on the dose (Helton, 1993).

For N Monte Carlo Runs

$$\text{Mean}(t_i) = \frac{\sum_{k=1}^{N} Dose_k(t_i)}{N}$$

where: (C8.1)

$Mean(t_i) \equiv$ mean dose at time t_i

$Dose_k(t_i) \equiv$ dose at time t_i, *for* run k

$t_i \equiv$ time in years

$i \equiv$ time steps (1 to 1000)

A reasonable strategy for assigning distributions for parameters used in Monte Carlo analyses is summarized below (Biwer et al., 2000):

- Select parameters to be assigned distributions - Not all parameters of the system under study require specification of a distribution. Those parameters that may well be distributed, but have little impact ultimately on the results, can be assigned constant values. Even if a parameter is known to have a significant effect on the results, its value may be specified at a constant value if it can be demonstrated that the choice leads to a conservative result.

- Assign distributions for important parameters - the assignment of parameter distributions usually is a matter of the quantity of available data:

- Ample data available - Where there are ample data, empirical distributions of a parameter can be generated directly.

- Sufficient data available - Data plotted as histograms or in probability coordinates can be used to identify standard distributional forms; e.g., normal, lognormal, uniform.

- Parameters with some data - Where there are insufficient data to estimate the shape of an empirical distribution, data may be supplemented by other soft information. For example, if there was a mechanistic basis for assigning a given distribution, or if a distribution was well known for the parameter on a regional basis, this information can be used to estimate the likely shape of the distribution. Alternatively, the new data can be used to supplement a prior, non-site-specific parameter distribution (e.g., Bayesian updating).

- Parameters with insufficient information - If sufficient data are not available, but there were other kinds of data that imply the likely behavior of a parameter, then it may be possible to supplement the desired data indirectly. An example of such a procedure is the use of root uptake factors to infer distribution coefficients in soil (Baes et al., 1984). If only incomplete information is known about the parameter (e.g., its mean, or its range), and no correlations to other types of data are available, then the choice of the parameter distribution should reflect the uncertainty. The distribution should have the least-biased value, which is generally a wide

distribution encompassing all of the possible values. One procedure to assure that the distribution has the least bias is known as the “maximum entropy formalism”, based on Shannon’s informational entropy (Harr, 1987). This formalism allows the investigator to pick the distribution based on the kinds of information available on the parameter to assure that the result is least-biased; for example, if only the range of the data is known, a uniform distribution between the range is least-biased. Table C8.1 describes the maximum entropy solutions for several classes of data (Harr, 1987). Other, empirical sources of guidance for choosing parameter distributions can be found in several other references (IAEA, 1989; NCRP, 1996a).

Table C8.1 Maximum Entropy Probability Distributions.
(Adapted from Harr, 1987)

Given Constraints on Data	Assigned Probability Density
minimum and maximum only	Uniform
Expected value only	Exponential
Expected value and standard deviation	Normal
Expected value, standard deviation, minimum and maximum	Beta
Mean occurrence rate between arrival of independent events	Poisson

! Parameter correlations - Many of the parameters used in the probabilistic analyses will be correlated to other parameters. Some parameter distributions may in fact be used to derive other distributions, e.g., root uptake factors may be used to derive soil distribution coefficients. Also, correlations are expected on physical principals, such as the relationship between hydraulic gradient and permeability. Where available, these correlation coefficients can then be used to generate correlated values of distributed parameters. This will help to avoid the situation where two correlated quantities are treated as uncorrelated, leading to unlikely combinations of parameters; e.g., high gradient and high hydraulic conductivity. The effects of assumed minimum versus assumed maximum levels of correlation can be investigated to evaluate the importance of including an explicit estimate of dependency between model parameters. In some cases, explicit modeling of the dependency between model parameters is possible, based on knowledge about the explicit mechanistic reasons for the dependencies. In general, it is more important to consider the effect of dependency when correlations are strong among the model’s most sensitive parameters (see discussion below on identifying sensitive parameters); weak correlations between sensitive parameters and strong correlations among insensitive parameters will generally have very little impact on the overall calculated dose (NCRP, 1996a).

8.5 Sensitivity Analysis

Uncertainty and sensitivity analyses are closely linked, and ideally, they should be considered together. The primary aim of a sensitivity analysis is to identify the input parameters that are the major contributors to the variation or uncertainty in the calculated dose. Identifying these key parameters is essential for building a defensible case in support of the assessment. In other words, it is very important for the analyst to justify the value or range of values used in the assessment to represent these key parameters. Several of the more-popular sensitivity methods used in other performance assessments conducted at NRC are presented below (NRC, 1999). It may be necessary for the analyst to use more than one approach in identifying the key parameters.

8.5.1 Deterministic Sensitivity Analysis

Two types of sensitivity analysis techniques are widely used; deterministic and Monte Carlo. The first, deterministic sensitivity analysis, calculates the change in the output result (i.e., peak dose) with respect to a small change in the independent variables, one at a time. The following formula illustrates the normalized sensitivity coefficient calculated from a deterministic analysis. Variable transformations, such as *normalization* used in this example, are described further in Section 8.5.3.1.

The advantage of the deterministic technique is that it is unambiguous in terms of demonstrating a cause and effect for the given conceptual model. The disadvantages are that at least one evaluation of the model must be performed for every independent variable, and the sensitivity result applies only locally; i.e., for one location in the space of all of the independent variables.

$$S_i = \left[\frac{\overline{X_i}}{\partial\left(\overline{X_i}\right)}\right]\left(\frac{\partial d}{\partial X_i}\right) \qquad \text{(C8.2)}$$

where:

$S_i \equiv$ sensitivity coefficient

$\overline{X_i} \equiv$ baseline value of the i^{th} parameter

$\partial d \equiv$ change in peak dose

$\partial X_i \equiv$ change in i^{th} parameter

8.5.2 Statistical Sensitivity Analysis techniques

The techniques used herein (except differential analysis) rely on the use of the Monte Carlo method for probabilistically determining system performance. Statistical analyses always start with a large pool of realizations (hundreds to thousands). Below is a compilation of some of the more-popular techniques for analyzing Monte Carlo results. It is recommended that the distribution of calculated doses at the time of the peak mean dose be used as the dependent variable in comparing against the input parameters. This allows an assessment of sensitivity in conjunction with the compliance demonstration; therefore, those parameters that most influence the compliance demonstration can be identified. In addition, it is recommended that the sensitivity of input parameter against the distribution of peak doses (i.e., the peak dose over time for each simulation) be considered. This will help to determine if there are key parameters controlling the time when the peak mean dose occurs and whether additional pathways and parameters are important to the compliance demonstration.

8.5.2.1 Scatter Plot and Linear Regression on One Variable

In the scatter plot/single linear regression technique, peak TEDE is plotted versus each of the sampled input variables. This is often a good starting point for examining Monte Carlo results because strong relationships between peak dose and the independent variables are often

$$t_i = m_i \sqrt{n \frac{S_{i,x}^2}{S^2}} \qquad \text{(C8.3)}$$

obvious. Single linear regression of Monte Carlo results may fail to show unambiguous correlation since other sampled parameters that affect the output are varying at the same time.

8.5.2.2 Use of the t-Statistic to Determine Significance of Single Linear Regression Parameters

The t-test estimates the confidence that an estimated parameter value differs from another value. In this case, it is used to determine if there is a specified (e.g., 95-percent) confidence that the slope (m_i) of a single linear regression is different from zero (Benjamin and Cornell, 1970).

The t statistic of the slope of the regression line is defined:

where

- t_i — t-statistic for regression coefficient i
- m_i — estimated value of regression coefficient (i.e., slope of the best-fit line for dose verus the independent variable i)
- S — estimated standard deviation of dose
- $S_{i,x}$ — estimated standard deviation of independent variable $\boldsymbol{x_i}$
- n number of samples

When the number of realizations is large, the t distribution may be represented by the normal distribution. The critical value to ensure 95-percent confidence that m_i differs from zero under these conditions is 1.96. Equation 8.3 is used therefore to determine whether the absolute value of the *t* statistic for each independent variable is greater than 1.96. If not, then the hypothesis that the independent variable is significant is rejected.

8.5.2.3 Partial rank correlation

The partial rank correlation coefficient measures the strength of the relationship between variables after any confounding influences of other variables have been removed. The partial rank correlation coefficient between X_1 and Y, with the influence of X_2 removed is given by:

$$\rho(X_1 Y X_2) = \frac{\rho_{X_1 Y} - \left(\rho_{X_1 X_2}\right)\left(\rho_{Y X_2}\right)}{\left[\left(1-\rho_{X_1 X_2}{}^2\right)\left(1-\rho_{Y X_2}{}^2\right)\right]^{1/2}} \qquad \text{(C8.4)}$$

where:

$\rho(X_1 Y X_2) \equiv$ partial rank correlation coefficient between X_1 and Y, with the influence of X_2 removed

$\rho_{X_1 Y} \equiv$ rank correlation coefficient between X_1 and Y

$\rho_{X_1 X_2} \equiv$ rank correlation coefficient between X_1 and X_2

$\rho_{Y X_2} \equiv$ rank correlation coefficient between Y and X_2

8.5.2.4 Stepwise Multiple Linear Regression

Stepwise multiple linear regression (stepwise regression) determines the most influential independent variables on output uncertainty according to how much each reduces the residual sum of squares (RSS) (Helton et al., 1991). The form of the regression equation is:

$$y = m_1 x_1 + m_2 x_2 + \ldots + m_n x_n + b \qquad \text{(C8.5)}$$

where

y — dependent variable (i.e., peak dose)
x_i — independent variables
m_i — regression coefficients
b — intercept

The variables may be the raw variables, transformed variables (e.g., logarithms), or ranks. The stepwise algorithm calculates the reduction in RSS for the independent variables in the order that gives the greatest reduction first. The regression coefficients m_i are the partial derivatives of

the dependent variable with respect to each of the independent variables; therefore, m_i provides a measure of the relative change in output with respect to a change in the input variable, given that the other input variables are held constant.

8.5.2.5 Non-parametric tests

Non-parametric tests differ from regression and differential analyses in that they do not require fitting the data to prespecified functional form. The Kolmogorov-Smirnov (KS) test is one such test that determines whether a set of samples has been drawn from a specific distribution (Bowen and Bennett, 1988). It is used to determine whether an independent variable is important by comparing a subset of the independent variable composed of the values from the highest category (e.g., 10 percent) of the peak TEDE realizations to the theoretical distribution of that independent variable. If the distributions are equivalent, then peak TEDE is not sensitive to the variable in question. Conversely, if the distributions are different, then the variable in question does have an effect on peak TEDE.

8.5.3 Variable Transformations and Their Attributes

Demonstrating the relationship among input and output variables can be enhanced by transforming the variables. This section describes some common variable transformations used in sensitivity analysis.

8.5.3.1 Normalization

In normalization, the input variable x_i is transformed by dividing by its mean value (or another baseline such as the median, 90th percentile, etc.):

Normalized variables are dimensionless and are scalar multiples of their baseline values.

$$x_i' = \frac{x_i}{\bar{x}_i} \qquad \text{(C8.6)}$$

Dimensionless variables allow the comparison of sensitivities to other independent variables with different dimensions. Normalized variables are a natural outcome of sensitivity derived from regression of log-transformed variables. Such sensitivity measures describe only the relative change in the dependent variable (peak TEDE) to changes in the independent variables. Although this is a useful measure, it treats all sensitivity results equally in spite of the value of peak TEDE. It may be more important to weight more heavily those results where absolute changes in peak TEDE are large. Furthermore, sensitivities calculated from normalized variables do not take into account the uncertainty in the independent variables.

8.5.3.2 Rank Transformation

Rank transformation, a dimensionless transform, replaces the value of a variable by its rank (i.e., the position in a list that has been sorted from largest to smallest values) (Iman and Conover, 1979). Analyses with ranks tend to show a greater sensitivity than results with untransformed variables, and diminish the influence of the tails in highly skewed distributions.

8.5.3.3 Logarithmic Transformation

For situations in which input and output variables range over many orders of magnitude, it may be advantageous or even necessary to perform analyses on the logarithm of the variables instead of the variable values themselves. The log transformation is also valuable for creating regression equations, where the subprocesses of the model multiply each other to form the output variable. For the present situation in which the dose calculation results from radionuclide releases from the waste form, transport through the geosphere, and uptake by humans, the processes are indeed largely multiplicative rather than additive. Log transforms therefore tend to give better fits to the Monte Carlo results than untransformed variables. The log transformation is generally used in conjunction with normalization.

8.5.3.4 Standardization

The independent and dependent variables can be standardized by subtracting the mean and dividing by the standard deviation, that is,

$$x_i' = \frac{x_i - \bar{x}}{s_x} \qquad \text{(C8.7)}$$

The advantage of standardization over normalization is that it inserts the approximate range of the variables into the sensitivity analyses. Therefore a variable that has a large per-unit sensitivity, but is well-known and has a narrow range, will have an increased sensitivity when standardized. Conversely, independent variables with wide ranges will show a reduced sensitivity when standardized.

Sensitivity measures based on standardized variables (standardized sensitivities) have the advantage of taking into account the uncertainty (in terms of the standard deviation) of the independent variable. This technique decreases the sensitivity if the range of the independent variable is large. Furthermore, the standardized sensitivities preserve the absolute values of peak TEDE since the derivatives are divided by the standard deviation for the entire set of calculations, rather than the mean peak TEDE at the evaluation point.

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